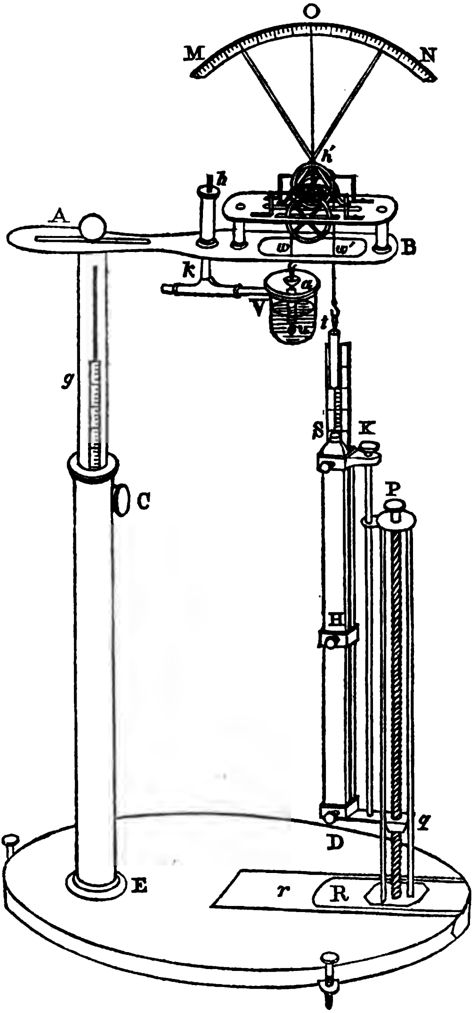

HARRIS'S HYDROSTATIC MAGNETOMETER. (FIG. 76.)

RUDIMENTARY

MAGNETISM:

BEING

A CONCISE EXPOSITION OF

THE

GENERAL PRINCIPLES OF MAGNETICAL SCIENCE

AND

THE PURPOSES TO WHICH IT HAS BEEN APPLIED.

With Ninety-seven Illustrations.

PARTS I. AND II.

BY

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PREFACE.

The many rich discoveries which have been made within a comparatively few years in the sister sciences of Electricity and Magnetism render it difficult to arrange, in a concise and rudimentary form, the various phenomena of one of these departments of physics, treated separately. Taking the term 'magnetism,' however, in its most general acceptation, the author proposes, in the *first* place, to put the student in possession of such elementary knowledge as bears directly on that species of force, peculiar to ferruginous matter, by which one particle of iron is observed to attract another particle at very sensible distances,—but without entering further into the combined sciences of electricity and magnetism than may be requisite to an adequate exposition of well-attested facts. It will also be desirable to combine with this statement a general history of the subject, considered as a distinct branch of physics. *Secondly*, it is proposed to describe the various magnetical instruments and manipulations necessary to the further prosecution of this wonderful and interesting subject; —thus completing the two Parts of the present Treatise.

In a Supplementary Treatise it is proposed to apply the knowledge thus acquired to a more extended investigation of

the great natural phenomena presented to us in the magnetic action of the earth, and to a further elucidation of certain practical benefits resulting from such inquiries. The work thus completed will be, as it professes, essentially rudimentary, but, nevertheless, without in any way compromising its scientific character. Its object is to illustrate and explain, theoretically and practically, and as familiarly as the nature of the subject will permit, a large class of natural phenomena intimately connected with the system of the world.

W. SNOW HARRIS.

Plymouth, August, 1850.

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RUDIMENTARY MAGNETISM.

I.

The Natural Magnet or Lodestone—Its general History—Nature and Properties—Communicative Power—Directive Power—Terms by which the Magnet has been characterized by various Nations—Magnetic Poles or Points of greatest Attraction—The Armed Magnet—Reciprocal Polar Attractions and Repulsions—Views of the Ancient Philosophers on the Nature of Magnetic Attraction—Modern Views.

1. THE earliest scientific records notice the operations of a subtle natural agency, peculiar in many respects to bodies containing iron, and acting more especially on iron and steel: by this agency ferruginous particles are drawn together, and frequently remain suspended one from the other in opposition to the force of gravity.

Notices of such phenomena are found in very ancient manuscripts, especially in those of China, and also in the writings of the Greek and Roman philosophers,—Thales, Pythagoras, Plato, Aristotle, Lucretius, Cicero, Pliny, and several others.

2. The existence of this subtle agency was first observed as a property of a mineral substance of a greyish or reddish black colour. The Greeks obtained it from the province of Magnesia, in Lydia, and termed it the *magnesian stone*, also μάγνης (magnes), from whence the modern terms *magnet* and *magnetism*, the one designating the mineral substance itself, the other, the peculiar agency supposed to reside in it. Hence also the term *magnetic attraction*, employed to characterize the power or force in operation.

3. The magnesian stone, or *native* magnet, abounds in various parts of the earth, especially in iron mines, where it is

found massive, frequently crystallized, and occasionally in beds of considerable thickness. Its constituents are, for the most part, oxygen and iron under the form of two oxides, the black and red. In 100 parts we have about 73 parts iron and 27 oxygen: it has been termed *magnetic iron ore*. Its colour varies from a reddish black to a deep grey. Native magnets from Arabia, China, and Bengal are commonly of a reddish colour, and are powerfully attractive. Those found in Germany and England have the colour of unwrought iron; those from Macedonia are more black and dull.

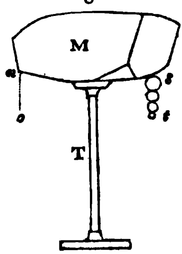
The specific gravity of magnetic iron ore is about 4½ times that of water, and affords, when worked, excellent bar iron.

The magnet is sometimes found in the form of small grains, constituting what has been termed *magnetic iron sand*. Magnetic sand abounds in the Isle of Sky, and in Fifeshire in Scotland. We find also in the iron mines of Norway a thick black earthy powder possessing magnetic properties.

4. This remarkable substance has not only the power of drawing apparently towards itself small particles of iron, and of holding suspended from various parts of its surface light rings and other small masses of iron or steel, but, as the ancients observed, it has also the important property of communicating or propagating, as it were, its own attractive power through a series of such rings or masses, so as to cause them to hang one on another in a sort of linked chain.

Exp. 1. In the annexed fig. 1, let the mass M be an irregular block of magnetic iron ore, mounted on any convenient support T; there will be found certain points, *n s*, on its surface so powerfully attractive as to sustain a series of short needles of iron *n o*, or a series of soft steel rings *s t*, which may be suspended successively one from the other solely by the force imparted to them from the magnet M.

Fig. 1.



5. In the celebrated philosophical poem 'De Rerum Natura,'

by the Roman poet Lucretius, who flourished about 60 years before the Christian era, we find the magnet, together with these illustrations of its power, very beautifully treated. Dr. Busby, in his translation of this poem, thus renders the passage:

> "Now, chief of all, the magnet's power I sing,
> And from what laws the attractive functions spring:
> The magnet's name the observing Grecians drew
> From the magnetic region where it grew;
> Its viewless potent virtues men surprise,
> Its strange effects they view with wondering eyes,
> When, without aid of hinges, links, or springs,
> A pendent chain we hold of steely rings
> Dropt from the stone—the stone the binding source,—
> Ring cleaves to ring, and owns magnetic force:
> Those held superior, those below maintain,
> Circle 'neath circle downward draws in vain,
> Whilst free in air disports the oscillating chain."

6. The attractive force of the magnet, as shown in this experiment, is found to reside principally in opposite points of its surface. These points have been termed *poles*, from another wondrous property of the magnet said to have been known to the inhabitants of China from time immemorial, but with which the philosophers of Greece and Rome were certainly not acquainted.

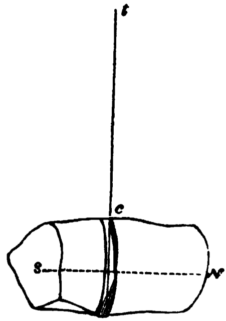
If the magnet be suspended by a delicate silk line from some point between the surfaces of attraction, so as to admit of its turning freely on that point, the mass will rest only in one position: this position will be such as to place its poles either in the line of the meridian, or very near it: one of the surfaces of the mass will have turned towards the north, and the opposite surface towards the south, and, if drawn aside from this position, will continue to vibrate backward and forward until it again rests in the same position.

In some very irregular and peculiar pieces of magnetic iron ore, several such poles have been observed, but they are always in opposite points of the mass; the native magnet, however, has generally two poles only.

Exp. 2. Immerse a piece of magnetic iron ore in fine iron or steel filings; the particles will be attracted, and will collect principally in separate and aggregated knots on certain opposite points of its surface.

Exp. 3. Having ascertained the position of the poles or points of greatest attraction, as at N S, fig. 2, trim the specimen in the direction of their axis or line N S, supposed to traverse the mass from one point to the other, so as to give it a somewhat oblong regular form, as represented in the figure. Suspend the mass by a fine thread of silk *c t* in some point *c*, intermediate and as central as possible between the poles N S; the mass will turn and rest in such a position as will place the extremities of the axis N S either in the direction of the meridian, or in a line varying from it by a given angular quantity either east or west, depending on the particular locality of the experiment, so that one of the poles, N, will have turned towards the north, and the opposite pole, S, towards the south, from which circumstance N has been called the *north*, and S the *south* pole of the magnet.

Fig. 2.



7. The property by which the magnet is caused to assume this particular position has been called magnetic *polarity* or *directive power*, and when the magnet is free to move into this position it is said *to traverse*.

A plane perpendicular to the horizon and passing through N S, the poles of the magnet whilst in their directive position is called the *plane of the magnetic meridian*. The line N S has been termed *the direction of the magnetic meridian*. The angle made between the line N S, or direction of the magnetic meridian, and the line of the true meridian of the place in which the magnet is suspended, has been termed the *variation* or *declination* of the magnet, or simply the *magnetic declination*.

8. The native magnet appears to have been known in almost every country, and at remote periods. The Jews were evidently acquainted with it. In the Talmud it is termed 'achzhàb'th,' the stone which attracts, and in their ancient prayers it has the European name magnēs. The term employed in different languages to designate the magnet, is, as may be readily imagined, commonly based upon its supposed "love of iron." Thus in the Chinese we have the term 'thsu-chy' or love stone, also 'hy-thy-chy,' the stone which snatches up iron. In the Siamese we have the term 'me-lek,' that which attracts iron. In the Sanscrit the magnet is termed 'ayaskânta,' loving toward iron. Euripides terms it 'lapis Herculaneus,' the Herculean stone, from its power over iron. Amongst the European languages we find in the French 'l'aimant' or the loving stone; in the Spanish 'iman.' In Hungarian we have again the term 'magnet kö,' the love stone; and so of a variety of others.

In several remarkable instances the magnet has been characterized by its directive property (6): thus in the Chinese we have the term 'tchu-chy,' the directing stone. In Tonkinin we have the term 'd'ànamtchûm,' the stone which shows the *south*. In Swedish we have 'segel-sten,' the seeing stone. In Icelandic 'leiderstein,' the leading stone, after the Saxon of 'lædan,' to *lead*, from whence the English name 'loadstone' or 'lodestone,' and by which term the magnet is commonly known in England. In a similar way we derive the term 'lodestar' or guiding star, as applied to the star of the pole; also the term *lode*, as applied to the leading vein in mining.

In a few instances the magnet has been named after the great hardness of its structure. The Greeks subsequently termed the magnet καλαμιτας, from whence the word 'kalamit' and *calamita* used by the early French writers, and employed by the Italians, and by some other European nations at the present day. In the Hebrew also we find occasionally the term 'kalmithath' and 'khalamish,' signifying hard, callous,

rocky. In the Roman we have the word 'adamas,' after the Greek αδαμαω, signifying unmalleable.*

9. The attractive force of the lodestone or natural magnet cannot generally be considered as of any great amount. Native magnets in their rude state will seldom lift their own weight, and with some rare exceptions their power is limited to a few pounds. The smallest magnets appear to have the greatest proportionate power. Sir Isaac Newton is said to have possessed a small magnet set in a ring, the weight of which was only 3 grains, but which supported by its attractive power on iron 700 grains; such instances, however, are by no means common. A native magnet presented by the Emperor of China to King John V. of Portugal, the weight of which was about 38 lbs., was found in February, 1781, to sustain above 200 lbs., or above five times its own weight.

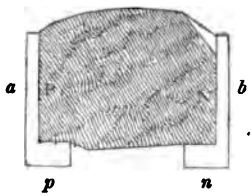
10. The effective power of the lodestone may be considerably improved by means of what is termed an *armature*, which consists of small pieces of very soft iron applied to the opposite polar surfaces of the stone, and projecting a little below it on each side. The attractive force is thus transmitted to the small projecting or artificial poles of iron (4): this is found not only to augment the power, but also to enable the experimentalist to bring both the poles to bear upon any given mass at the same instant.

In arming a lodestone in this way, care must be taken to select a piece of magnetic iron ore having two poles (6) and possessing some considerable power. The opposite faces P N, fig. 3, in which the poles reside, should be squared off by a lapidary's wheel, and made smooth and regular, and in some cases it may be desirable to trim the specimen and give a regular form to the whole block, keeping the distance of the poles P N or axis N S, fig. 2, as great as possible.†

* For a valuable and comprehensive dissertation on this subject by T. S. Davies, Esq., F.R.S., see Thomson's 'Scientific Annual' for 1837, page 250.

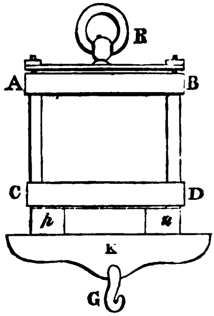
† The native magnet being of a callous and close texture, sufficiently

Fig. 3.



The pieces intended for the armature should be made of very soft iron, and each formed with a vertical face about $\frac{1}{8}$th to $\frac{1}{4}$th of an inch thick, with a projecting solid foot below, as at *a p* and *b n*, fig. 3; the vertical face being closely applied to the polar surfaces, and the mass allowed to rest on the projecting feet *p n*, forming the artificial poles. Things being thus arranged, the whole is bound firmly together by a cap of silver or brass, or by plain metallic bands, as represented in A B and C D, fig. 4.

Fig. 4.



A ring R is usually fixed in the upper part of the cap for the convenience of raising the whole mass, and a transverse piece of soft iron K, termed a keeper or lifter, furnished with a central hook G, is placed across the artificial poles *p n*, so as to unite them. This keeper is found to preserve and increase the attractive force of the poles, especially if the magnet be suspended by its upper ring R, and weights be attached to the hook G, and by which its power may be roughly estimated.

If the armed magnet be thus suspended, and a small scale-pan attached to the keeper K, an additional weight may be added daily for a considerable time: the lodestone thus armed may be caused to sustain from twenty to thirty times its own weight.

When an armed lodestone is employed for particular experimental inquiries or other purposes, the keeper K may be removed, but it should be replaced when the magnet is not in use.

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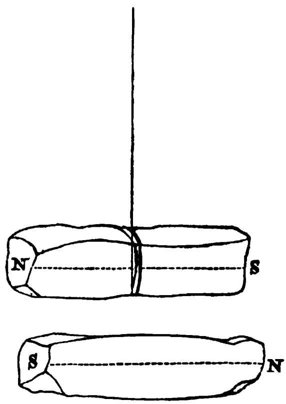
hard to afford sparks when struck against steel, is difficult to work with common tools. It may, however, be trimmed into form by means of a lapidary's wheel, or other wheels employed in cutting and grinding glass.

11. Although the attraction of the magnet for iron may be considered as its most general and characteristic property, yet this property has not been found so universal as to be without very remarkable exceptions; the exceptions being such as to involve what at first appears a totally opposite and different kind of power. Pliny, in the 36th book of his Natural History, has an obscure allusion to such a power: "There is (he says) a kind of stone in Ethiopia, which will not abide iron, but repulses and driveth iron away from it."* Marcellus, an empirical physician, who flourished under the Emperor Theodosius, about the year 400 of our era, alludes to the magnet as the attractor and repulsor of iron.

It is, however, very doubtful whether the ancients were fully acquainted with the properties of magnetic repulsion, such as now observed. Lucretius, who was certainly well acquainted with the history of science up to his time, is quite silent upon this subject. The discovery, therefore, of the repulsive power of the magnet is, in all probability, of very modern date.

Fig. 5.



If we suspend a magnet by a fine silk fibre over another magnet, or near another magnet also suspended, the poles of these magnets will arrange themselves in such a way as to bring the opposite poles together; the similar poles are found so powerfully and reciprocally repulsive, as not to allow the masses to rest with their similar poles in juxtaposition.

Exp. 4. Procure two small masses of magnetic iron ore,

* "Alius rursus in eadem Ethiopia non procul mons gignit lapidem theamedem, qui ferrum omne abigit respuitque."

and having determined the position of the poles (6), prepare the pieces as before described (6), and suspend one over the other, as in the annexed figure 5. The north poles N N will be found to arrange themselves immediately opposite the south poles S S, and so decidedly, that the suspended magnet N S will not rest in any other position.

12. We perceive, then, by this experiment that a repellent magnetic force is attendant on magnetic polarity, and that consequently any mass of iron having fixed polarity (7) would be repulsed by the magnet whenever the like poles were opposed to each other. Now the polarity of the lodestone is altogether dependent on the iron it contains; and we should therefore expect to find common iron possessing, in certain instances, similar properties to those of the magnet. Such cases would be attended by the development of a new and opposite force, not observed in the ordinary operations of the magnet on ferruginous matter. It is well known that pieces of common iron, which have been for a great length of time in one fixed position, or underground, acquire considerable polarity,—in fact, become magnets: this very frequently happens with old turret vane-spindles, and the old rusty bars of abbey windows. In the 'Memoirs of the Academy of Sciences' for 1731, we find an account of a large bell at Marseilles having an axis of iron: this axis rested on stone blocks, and threw off from time to time great quantities of rust, which, mixing with the particles of stone and the oil used to facilitate the motion, became conglomerated into a hardened mass: this mass had all the properties of the native magnet. The bell is supposed to have been in the same position for 400 years.

This curious fact not only serves to elucidate the early observations of the magnet's repulsion for iron, but it throws further light on the probable source of the polarity of the magnet itself.

13. The views of the ancient philosophers respecting the immediate source of the power of the magnet were such as, on a first acquaintance with the phenomena, might have been

anticipated. Directing their attention to occult causes, they were driven to assume the existence of a peculiar essence or effluvium, which, being emitted by the magnet, dragged the iron, as it were, into its embrace. Lucretius advances a step further upon this crude idea, and supposes that the magnetic effluvium drives the air out of the space existing between the magnet and a piece of steel or iron, and, by thus producing a vacuum, causes the iron to be pressed towards the magnet. In his poem we find the following lines, as translated by Busby:

> " Soon shall we trace by what mysterious laws,
> What secret energy, what latent cause,
> Steel, the strong magnet, actuates and draws.
> First, then, my loved illustrious Memnon, know,
> Ceaseless effluvia from the magnet flow,—
> Effluvia, whose superior powers expel
> The air that lies between the stone and steel.
> A vacuum formed, the steely atoms fly
> In a link'd train, and all the void supply;
> While the whole ring to which the train is join'd,
> The influence owns, and follows close behind."

Thales, the celebrated philosopher of Miletus, conceived the magnet to be endowed with a sort of immaterial spirit, and to possess a species of animation.

14. Leaving for the present, however, all such metaphysical speculations, it will be sufficient to recognize the important fact, that whatever be the hidden cause of magnetic phenomena, it may with safety be inferred, from the attractions and repulsions of similar and dissimilar poles just described (11), that the direct practical consequence of magnetic polarity is the development of two dissimilar and distinct forces, repulsive of themselves, but attractive of each other. It is with these two forces, and the laws of their action, that the experimentalist and mathematician is more immediately concerned: they have been accordingly considered as positive and negative forces, and have been characterized by the positive and negative signs. These forces have been also termed

north and south polarities, or magnetism, as expressive of their mutual relations to the directive property of the magnet. The following simple formula expresses concisely the fundamental law of their reciprocal action,—"Similar polarities repel, opposite polarities attract each other."

15. The student will perceive, that in assuming the existence of these opposite forces, he is merely expressing a fact totally independent of all metaphysical speculation.

From whatever source the forces may arise, that would in no way affect their existence as mechanical qualities. In look-through the operations of other hidden principles of nature, we find in all of them what may be considered as opposite or antagonistic qualities. Thus we have light and darkness, heat and cold, gravity and levity, action and reaction, &c. Now, although it be proved that no positive principles, such as darkness, cold, levity, &c. have existence, yet, taken as the negatives of light, heat, gravity, &c., we could, if it were requisite, represent and employ darkness, cold, levity, &c. as so many antagonistic forces. If I mix a certain quantity of hot water with a certain quantity of ice, I may, in a certain sense, be said to mix heat and cold together; and the resulting temperature would be either a neutral temperature, as referred to a given standard, or it would be in excess or defect of such a standard, and might be faithfully characterized either by zero or by the positive or negative signs, to denote the excess or deficiency in relation to this standard. In the present imperfect state of our knowledge of the cause of electrical and magnetic forces, it is at least useful and convenient to consider these forces under this form, with a view of better representing to the mind the laws of magnetic action, and linking into an intelligible chain the several phenomena presented to us.

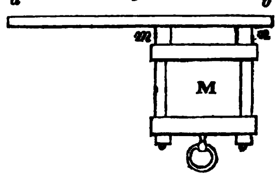
II.

The Artificial Magnet—How produced—Various Forms and Methods of Magnetizing—Properties of a Magnetic Bar—It assumes a definite Position of Direction and Inclination—Its Force variable in different points of its Length—Magnetic Centre, Axis, and Poles—Attraction and Repulsion of the opposite Polar Forces—Lines of Magnetic Force—Reciprocal Action of Magnetic Bars on each other—Magnetic Induction or Influence—Reactive Force of Iron on Magnets.

16. THE communicative property of the lodestone (4) may be considered as the great source of the advances and of many of the grand modern discoveries achieved in this interesting department of science; for although the attractive property communicated to soft iron or steel by contact with the lodestone (fig. 1, p. 2) commonly vanishes so soon as the iron is removed from the magnetic pole, yet in many remarkable instances the attractive power, together with all the properties of the original magnet, remain, and we obtain what has been termed an *artificial magnet.*

Exp. 5. Procure a small bar of steel about 8 inches in length, $\frac{1}{4}$th of an inch wide, and $\frac{1}{8}$th of an inch thick, or a piece of common steel wire of commerce of about the same length and from $\frac{1}{8}$th to $\frac{1}{4}$th of an inch in diameter. Let the steel be well hardened and tempered by plunging it at a cherry-red heat into cold water; when cold and polished, apply each extremity in succession to the opposite poles of an armed magnet (10), fig. 3, first touching with gentle friction one extremity of the bar, or one of the poles and the opposite extremity on the other pole, or, which is better, draw the bar *a b*, fig. 6, a few times, in the direction of

Fig. 6.



its length, across the two poles *m n* of the magnet M, as represented in the figure, and in such a way as not to pass either extremity, *a b*, beyond or off the opposite poles *m n*; finally, bring the bar *a b* so as to rest with its extremity *a b* equally distant from each pole *m n*; that is to say, bring the poles *m n* at the centre of the bar, or as nearly as may be. In this position remove the bar from the poles. The bar will now be found attractive of particles of iron, common steel needles, and other ferruginous matter: when suspended it will arrange itself in the direction of the magnetic meridian (7), and will, in fact, have all the properties of the lodestone (6, 10, 11), including the important property of imparting or exciting a magnetic condition in tempered steel.

Exp. 6. Take a small bar of steel which has been rendered magnetic by the process just described (Exp. 5), apply it with slight friction to a piece of hard steel wire or a similar bar, and in such way that the opposite extremities of each bar may have contact attended by a slight degree of friction: this second bar or wire will be found also to have acquired a similar magnetic condition to the first; and this process may be continued from the second to a third wire of steel, and so on without limit.

The propagation of magnetism from one bar of steel to another, as illustrated in this experiment, enables the experimentalist to obtain artificial magnets to any given amount; and since the form and magnitude of the steel has not been found to interfere with the generality of the result, we are further enabled to obtain magnets of any required figure or magnitude.

17. It is to be especially observed that the polarities (14) excited in the opposite portions of a steel bar by this artificial process of magnetizing (16) are the reverse of those of the magnetic poles to which these portions have been applied (16). Thus in Exp. 5, fig. 6, if the extremity *b* of the steel *a b*, rest on the north or positive pole *n* of the magnet M; the polarity induced in that extremity *b*, will be a south or

negative polarity (14). Reciprocally, if the extremity *n* be brought to rest on the negative or south pole *m*, then the polarity induced in that point of the steel will be a positive or north polarity.

This result may be conceived to depend upon the general principle already explained (14), viz. that the north magnetism of the pole, *n*, of the magnet repels the similar or north magnetism of the bar, and attracts the south,—and reciprocally the south magnetism of the pole *m* repels the similar magnetism of the bar, and attracts the north: hence the two positive and negative elements (14) resident in the bar have become disunited, and caused to appear as two separate and distinct forces. Hence it has been found desirable for practical purposes to mark one extremity of an artificial magnet with a small file cut, carried round the bar: the marked end is generally that extremity which points north when the magnet is suspended. This means of distinguishing the two poles is found of great importance in practical magnetism.

18. Magnetized steel was in all probability first obtained in the way just described (16), as may be inferred from several terms used by the Chinese and other Indian nations to designate the magnet. One of these, used by the Chinese and Japanese, refers to the magnet as the 'stone for rubbing the needle;' others call it the 'stone for the steel needle:' the native magnet, however, is not the only source of magnetism in steel; it is now found that a magnetic condition may be excited in hard steel by various mechanical processes, such as filing, hammering, drilling, and the like; also by changes of temperature, as in the heating and cooling of iron; likewise by mere position alone; finally, by Voltaic or common electricity.

19. We have now arrived at a complete notion of an artificial magnet, which, as we see (16), consists of a mass of hard steel possessing all the properties of the lodestone, and which have been imparted to it by artificial means.

Artificial magnets, as just observed, may be of any re-

quired form, or of almost any dimensions, according to the particular views of the experimentalist: for general purposes they are limited to straight bars, such as represented in fig. 7, or otherwise to bars bent into a curvilinear form, resembling a horse-shoe, as in fig. 8; the branches *c p* and *c n* being longer, and the extremities *p n* nearer than in the common horse-shoe. Many such bars, either straight or curved, form, when combined, what is termed a ***compound magnet***, such, for example, as that represented in figs. 9 and 10. The combination of several compound magnets with projecting armatures (10) constitutes a ***magnetic battery*** or ***machine***. The dimensions well adapted to magnetic bars, either straight or curved, are such as to give the breadth about $\frac{1}{14}$th or $\frac{1}{15}$th of the length, and the thickness something less or not exceeding one half of the breadth.

Fig. 7.

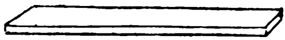


Fig 8.

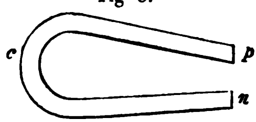
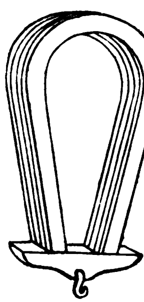


Fig. 9.

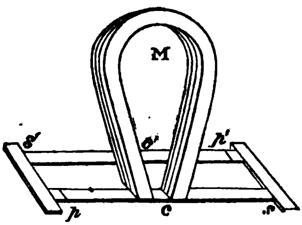
Fig. 10.



20. Although the simple method of magnetizing we have just described (16, Exp. 5), is sufficient for small bars, plates, or cylinders of steel, yet it is not equally applicable when required for the production of a high degree of power in artificial magnets of considerable magnitude. To obtain this, several methods of magnetizing, to be hereafter noticed, have been proposed: it may, however, be at present sufficient to describe the following,—the best perhaps of any for general practical purposes.

Let it be required, for example, to magnetize two straight bars of highly tempered steel, fig. 7. Place the bars *p s*, *p′ s′*, fig. 11, on a flat board between two pieces of soft iron, *p s′*, *p′ s*, about 6 inches in length, and of the same breadth and depth as the bars, and in such a way that the opposite marked extremities, *p p′*, may be in opposite angles of the parallelogram *p p′*. This arrangement being made, and the parallelogram secured in its position, apply an armed magnet, or, what is better, a combination of magnetical horse-shoe bars M, to one end, *s*, of either of the bars *p s*, taking care, on the principle explained (16), to place the compound magnet M on the bars in such a way that its marked pole will rest next the unmarked extremity, *s*, of the bar, or conversely if placed on the marked extremity, *p*, of one of the bars; then the opposite or unmarked pole of the compound magnet M may rest next the marked pole *p*. Things being thus arranged, continue to slide the magnet upon the bar, carrying it completely round the whole parallelogram in one direction, *s p*, *s′ p′*, and stopping finally in the centre, *c*, of one of the bars. Repeat this process on each face of the bars, and a very high degree of force will be found to have been produced; the whole parallelogram will hang together, and each bar, on separating the keepers, *p s′*, *s p′*, will have acquired a high amount of permanent magnetism.

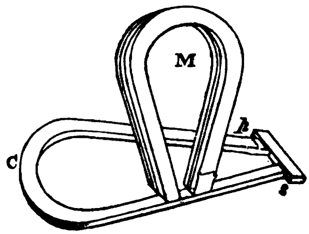
Fig. 11.



To magnetize a bar of tempered steel, fig. 8, curved into the horse-shoe form, fix the bar, fig. 12, on a flat board, with its extremities, *p s*, against a straight piece of soft iron, *p s*, of the same thickness and width as the bar. Having secured the whole in this position, place a compound magnet M, or an armed native magnet, on one of the extremities, *s*, of the curved bar, taking care that the opposite

or marked and unmarked ends are in contact with each other. Continue as before to glide the magnet M several times round the whole series, and in the same direction, *s c p*, finally stopping in the centre, *c*. Repeat this process on each face of the bar, when a high degree of power will have become developed; so much so, that the iron or keeper *p s* cannot be directly pulled away without considerable force, and in some instances cannot be conveniently removed except by sliding it off.

Fig. 12.



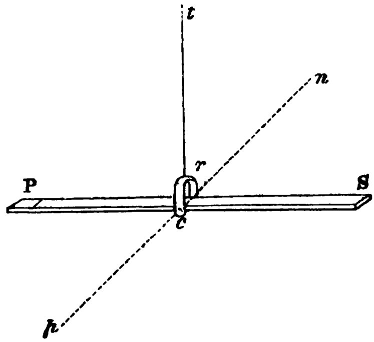
In order to preserve effectually the magnetism thus excited in bars of steel, it is requisite, when not in use, to keep their opposite poles united by means of pieces of soft iron; that is, in the same way precisely as in the process of magnetizing shown in figs. 11 and 12.

21. *Properties of a magnetic bar.* If a bar of tempered steel be carefully prepared, and poised upon a central point so as to be indifferent as to position, and further be so balanced and suspended as to be at liberty to move in a horizontal plane, then, on being rendered magnetic (16), it will be no longer indifferent as to position, but will gradually settle in a plane either passing immediately through the meridian of the place or differing from it by a given angular quantity: if turned aside from this direction, and again set free, it will continue to oscillate across the meridian backwards and forwards, until it again rests in the same position, as in the case of the native magnet (6). If the bar be also at liberty to move in a vertical plane, then, whilst turning into this meridional plane, it will at the same time incline or dip one of its extremities below the horizontal line, which in these latitudes amounts to an angle of nearly 70 degrees. The extremity which thus dips, is, in latitude north of the equator, turned towards the north

pole of the earth, and, in latitudes south of the equator, towards the south pole of the earth. The inclination increases as we proceed north or south from a certain great circle of the sphere traversing the equatorial parts of our globe, and in which the inclination is nothing.

Exp. 7. Take a perfectly straight and even bar of steel, P S, fig. 13, sufficiently hard to retain a magnetic state. It may be 7 inches long, $\frac{1}{8}$th of an inch wide, and $\frac{1}{10}$th of an inch thick. Drill a clean hole through the centre of the wide surface, and then pass an extremely fine drill also through the centre transversely to this hole, across the thickness of the bar, edgewise, and so accurately as to pass through the centre of gravity of the mass, or as nearly as possible; proceed now to complete the equilibrium of the bar upon a fine needle as an axis, and in such a way as to render it indifferent as to position in a vertical plane or nearly so, and that whether it be placed with one or the other face uppermost. Let the bar be now magnetized (16), and then mounted on its central axis; run the axis through a small silver stirrup *c r*, and suspend the whole by a fine silk fibre *r t*, attached to a fixed point *t*; the bar P S will be observed gradually to assume a definite and oblique position, *p n*, inclining in these latitudes its north pole, P, nearly 70 degrees below the horizontal line, turning at the same time into a plane deviating from the plane of the meridian by a given angular quantity; the lower extremity having turned towards the north, and the other extremity

Fig. 13.



towards the south; and it may be likewise observed, on the principle already stated (17), that the extremities which have thus turned the one towards the north and the other towards the south, will have been derived from the opposite poles of the lodestone or magnet by which it has been magnetized.

22. This experiment requires considerable mechanical skill and care in the preparation and balance of the bar, so as to poise it accurately about its centre of gravity: a very straight piece of cylindrical steel wire, which is generally sufficiently hard to retain polarity, may be employed for the purpose, or the steel of which the bar is made may be also rendered sufficiently hard to retain a magnetic state by simple hammering on the anvil, and yet admit of its being drilled and worked. The process of hardening after the requisite balance has been effected is liable to warp the steel and vitiate the experiment. We may, if we thought it desirable, harden the extremities only, by dipping them at a cherry-red heat into cold water; but for this and the following experiments it is desirable to employ naturally hard steel.

23. If the bar be again applied to the lodestone or magnet, but in a direction the reverse of that by which its previous magnetic condition was excited (16, Experiment 5), that is to say, if the north pole of the bar rest on the north pole of the lodestone, and the south pole on the south pole of the lodestone, then if the experiment be carefully made, we may totally and exactly destroy the magnetism previously excited, or, by continuing the magnetizing process (16), reverse the poles and magnetize the bar in the opposite direction, that is to say, induce a north pole in the extremity which was before a south pole, and a south pole in the extremity which was before a north pole.

Exp. 8. Let the bar be rendered neutral by an equal and reverse process of magnetizing (16); replace it on the axis as before, Experiment 7: it will be again indifferent as to position, and will remain perfectly horizontal.

Exp. 9. Pass the bar across the poles of the lodestone

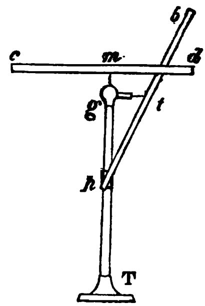
(16) so as to magnetize it in an opposite direction to that in the former experiment (7); replace the bar on its axis, the phenomena before observed (21) will re-appear, but the extremity which before inclined and pointed north, will now be raised and will point south, and conversely the extremity which was before raised and pointed south, will now be inclined and will point north.

It is not difficult, after a little experience, to destroy exactly the previous magnetism by an equal and reverse process of magnetizing (16): it may be minutely affected by small final contacts with the similar pole of the lodestone, so as to cause the similar polarities to repulse and destroy each other (14); the neutrality may be considered as having been sufficiently effected if on plunging the ends of the bar into soft iron filings, the filings do not adhere magnetically to the poles.

24. As the perfect success of the preceding experiments requires very great mechanical skill in the construction and adjustment of the needle or bar, it may be desirable to describe a less difficult means of observing the mere facts of the dip and direction by two distinct and simple processes.

It will be convenient, for experiments of this kind, to employ a stand or support, the altitude of which may be varied, such as is represented in the annexed figure 14, in which *p g* is a light tube of brass, sliding with friction within a second tube *p* T. The extremity *g* of the sliding part gives support to a fine vertical and pointed needle *g m*, upon which a horizontal magnetic bar *c d* may be delicately suspended; and also to a short horizontal arm, also terminating in a short, fine, and pointed needle, upon which a bar *p b* may be suspended so as to traverse in a vertical plane. The whole is supported on a firm foot T.

Fig. 14.



Exp. 10. Poise a light steel bar *p b*, fig. 14, similar to

that employed in the former experiments, on the short horizontal axis, the pivot-hole passing nearly but not quite through the bar edgewise, and in such way as to rest horizontally with either face upwards.

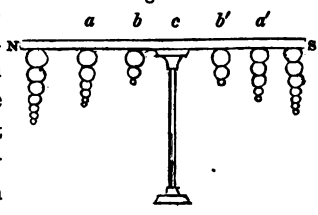
Prepare a second similar bar *c d*, and having magnetized it, balance it horizontally on the fine needle *g m*; the bar *p b* being removed, this bar *c d* will arrange itself in the direction of the magnetic meridian (7), with all the attendant circumstances before described (16). The direction *c d* being determined, turn the stand until the arm *g t* is at right angles to the direction *c d*; remove the magnetized bar *c d*, and magnetize and place the balanced bar *p b* on the fine pivot axis; the bar will then assume an oblique position, and all the general phenomena of the inclination may be observed as before described, Experiment 7.

This dip or inclination, together with the direction of the magnetic needle, is not every where alike, especially the dip, which varies from the equatorial parts of our globe where it is 0, to the polar regions where it is a maximum or 90°. The direction is less variable, it being in some places a little to the east of the north, in others a little to the west, and in some points of the earth's surface there is no variation.

25. The force developed in a bar of steel rendered magnetic by artificial means, is greatest at the two extremities or poles of the bar, from whence it is found to decrease toward the centre, or some point intermediate between the two poles in which the force is no longer apparent.

Exp. 11. Take a powerful magnetic bar N S, fig. 15, about 2 feet in length, an inch wide, and $\frac{3}{10}$ths of an inch thick. Let this bar be equally hardened throughout its length, and be uniformly magnetized. Place it on an elevated point of support *c*, as

Fig. 15.



represented in the figure. Apply now at each extremity N S, and at any given points *a b*, and *a′ b′*, intermediate between the extremities N S, and the centre *c*, a series of small rings of soft iron wire, varying from $\frac{3}{4}$ of an inch to a $\frac{1}{4}$ of an inch in diameter, and formed of wire of $\frac{1}{8}$th to $\frac{1}{16}$th of an inch in thickness. The number of rings of equal size which may be thus suspended in series (4), will vary throughout the distance between the centre *c*, and either extremity N S, of the bar. The number which can be sustained at the poles N S, being greater than at points *a a′*, nearer the centre, and the number which can be supported at certain points *a a′*, will be greater than the number which can be supported at other points *b b′*, within these, nearer the centre *c*, and so on until we arrive at a point *c*, in which no attractive force is apparent.

The variable attractive force between the centre and poles of the magnetic bar may be very beautifully observed by the simple balance, described at page 34, fig. 29. By passing the bar from point to point under the suspended iron, and regulating the distance to the same point by a divided scale, the increased attraction on each point, as we approach either pole, may be minutely determined. We have only to select such distances as will enable us to observe the increasing force without oversetting the beam of the balance.

26. The points in which the force is absolutely at zero will be found in a line passing across the surface of the bar transversely to its length, and, if the bar have been carefully magnetized (16), will divide it into two equal parts. It will consequently be at the centre of the bar. This line has been termed the *mean* or *neutral line* of that surface. In a similar way the points of greatest attraction will be found in two similar lines parallel to the mean line and at each extremity of the bar: these lines have been termed the *lines of the poles*. A line passing longitudinally through the centre of the mean and polar lines, and dividing the bar into equal longitudinal parts, has been termed the *axial line* of that surface. The

point of intersection of the axial and mean lines has been termed the *magnetic centre,* and of the axial and polar lines, the *magnetic poles* of that surface.

If each surface of the bar be similarly magnetized (20), so that the magnetism of the opposite and homologous points is equally and similarly developed, then all these points and lines on each surface may be taken to coincide and concentrate in the substance of the bar, giving to the bar an ideal transverse and longitudinal magnetic axis, or a magnetic centre and two magnetic poles.

The term *pole,* it is to be observed, has been occasionally employed in other senses; each half of the bar, for example, has been termed a *pole.* It has been also used to designate a sort of ideal point within each extremity of the bar, in which all the forces may be conceived to be collected, and to be the same as if proceeding from every point of each polar half of the bar,—much in the same way as we conceive the existence of a point of concentration of force within any material substance, and which we term the centre of gravity.

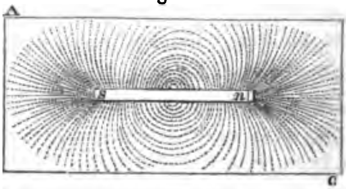
27. In magnetizing a bar of hardened steel by artificial magnets (21), it is requisite to touch each surface in precisely the same way, and stop the process exactly at the centre (21); that is, if we require each surface to be alike and the bar to be rendered uniformly magnetic from its centre to the extremities: in, fact the superficial boundaries of a bar of steel, of very sensible thickness, may be considered, when magnetized in the common way (21), as so many distinct laminæ, each of which may be taken magnetically as separate systems, so that the centre and poles of the one surface may fall differently to those of the other. It is by no means easy to obtain a magnetic bar extremely perfect as an experimental agent. We require, in the first place, steel of a uniform texture and equally hard in every point, and to be magnetized in such way as to render the magnetic condition of each surface identical and coincident.

28. The position of the magnetic centre and poles of each

surface, together with the general magnetic condition of the bar, and the reciprocal attractions, repulsions, and neutralization of the opposite forces (14), may be very beautifully shown in the following way.

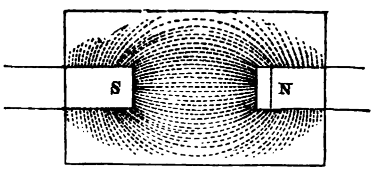
Exp. 12. Strain a piece of common drawing paper on an open frame A C, fig. 16, and place it over a hard steel bar S N, regularly and powerfully magnetic; project on the paper over the bar, through a small muslin or lawn sieve, some fine iron dust or filings; the particles will arrange themselves in a series of curved lines of magnetic force proceeding from homologous or similar points on each side of the middle of the bar, some uniting about the magnetic centre, others standing out at the extremities as if repelled from the poles N S, and tending to turn at considerable distances into other curved lines of force, to unite their branches between the opposite poles. This experiment may be rendered more decisive by slightly tapping the finger on the paper, so as to give the particles a little vibration.

Fig. 16.



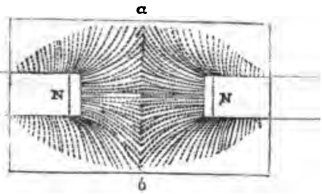
Exp. 13. Oppose the dissimilar poles S N, fig. 17, of two powerful bars to each other at about 2 inches distance, and project over them fine iron filings as before; similar results ensue. Magnetic lines of force, both straight and curved, and proceeding from similar points of each bar, will be apparent, uniting the two poles by chains of reciprocal attraction.

Fig. 17.



Exp. 14. Change the position of one of the bars, so as to oppose two similar poles N N, fig. 18; the lines of force will then appear to be conflicting lines; the repulsive forces will cause a straight line *a b* to appear on the open space or field between the poles, from which the iron dust stands out transversely. At this line, the opposed forces on either side are apparently struggling with each other, being exerted in repulsive directions from the opposed poles.

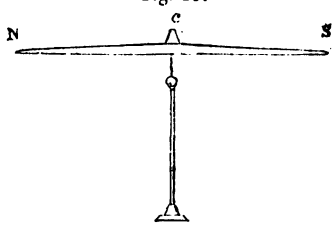
Fig. 18.



We have in these phenomena satisfactory visual evidence of the existence of two distinct forces,—of their reciprocal attractions and repulsions, and their mutual neutralization.

29. A light magnetic bar N S, fig. 19, or a small magnetic steel cylinder, of great comparative length, has been termed a *magnetic needle*. When delicately poised on a central point *c*, so as to retain a horizontal position, and move freely in a horizontal plane, it has been termed the *horizontal needle*. When poised on a fine central axis *t*, fig. 14, so as to move freely in a vertical plane, it has been termed a *vertical* or *dipping needle*. If suspended as in fig. 13, so as to have motion in both a horizontal and vertical plane, it has been termed the *horizontal and vertical needle*.

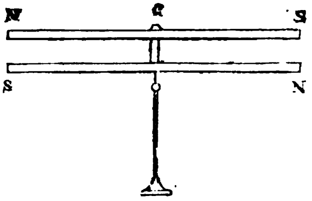
Fig. 19.



Two needles N S, N S, fig. 20, precisely equal and similar, poised upon a fine centre *c*, and fixed to each other with their opposite poles N S, S N, one immediately over the other, form

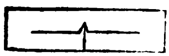
what is termed an *astatic needle*. In this combination, the directive force of the needles (7) may be considered as being altogether neutralized, or nearly so; since it is not only exerted in two equal and opposite directions, but the dissimilar polarities N S, S N tend to neutralize each other.

Fig. 20.



30. Instruments for ascertaining whether a substance has polarity or not, and for detecting the presence and kind of force in operation, have been termed *magnetoscopes*. The horizontal, vertical, and astatic needles (29), may be considered as instruments of this kind. The most simple kind of magnetoscope is a small horizontal needle, about an inch in length, delicately suspended by a fine silk fibre, or otherwise set upon a fine point and agate centre, within a small wood or glass case, as represented in the annexed fig. 21, and so set as to admit of some degree of dip or depression of either pole, as well as a perfect motion in a horizontal plane. From the attractive and repulsive forces of similar and dissimilar poles (14), it is evident, from the kind of effect produced on the poles of the magnetoscope, we may always determine the presence or kind of polarity acting on it. Thus, if such an instrument as that just described, fig. 21, be glided along the surface of any given substance without any attractive or repulsive effect being apparent, such a substance may be considered as non-magnetic. If, on the contrary, we find both poles of the instrument every where attracted indifferently, then we may infer that the substance is a magnetic substance: such would be the case with a piece of common soft iron. Should we find certain points attractive of one of the poles of the small needle, and repulsive of the other, then we may infer that not only is the substance a magnetic substance, but that it has also polarity, or is a magnet.

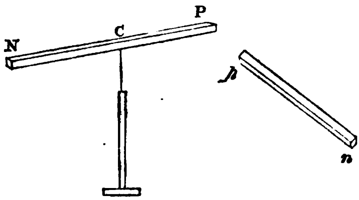
Fig. 21.



RECIPROCAL ACTION OF MAGNETIC BARS.

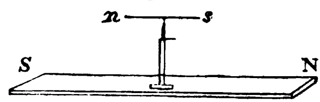
31. If a magnetic bar be poised horizontally on a central point (29), and a piece of soft iron be presented to it, the iron will be found attractive of either pole. Such, however, is not the case on presenting to it a piece of magnetic steel. In this case, as in that of the native magnet (11), fig. 5, Exp. 4, it is found that the similar poles, or those which, when the masses are suspended, point in the same direction, repel each other; whilst the opposite or dissimilar poles attract.

Fig. 22.



Exp. 15. Suspend a magnetic bar N P, fig. 22, on a fine centre *c*, and present to one of its poles P the similar pole *p* of a second bar *p n*, the pole P will immediately recede, and be apparently repulsed: present the pole *p* to the opposite pole N, the reverse of this will ensue,—the bar N P will be apparently attracted.

Fig. 23.



Exp. 16. Place a magnetic needle or bar *n s*, fig. 23, immediately over a strongly magnetized bar S N: the needle, as in Exp. 4 (11), with the native magnet, will rest in no other direction but that in which the opposite poles S *n* and *s* N are opposed to each other.

32. These reciprocal attractions and repulsions may be taken as further evidence of the operation of two opposite forces, or magnetic elements, repulsive of themselves, but attractive of each other (14), and which, when intimately combined, exactly neutralize or compensate their respective attractions and repulsions, constituting, in their combined state, what may be termed the *latent* magnetism of the bar. When

separate, and removed in a greater or less degree from their reciprocal influence, they become more or less active, and are thus in a condition to operate on the latent magnetism of other ferruginous matter (4). The neutralization of these forces, and their tendency to unite, is well illustrated in the following way.

Exp. 17. Place a short piece of soft iron T, fig. 24, about 5 inches long, in contact with a powerful magnetic bar M, which may be about 2 feet in length (19). Suspend from the iron T, by the attractive force communicated to it (4), a steel or iron ring *r*. Under these circumstances, let a second similar bar M′, fig. 25, be applied to the opposite extremity of the iron T, and in such a way that the dissimilar poles *n s* of the two bars may operate on each other through the substance of the iron: the result will be, that the two magnetic elements will so exactly neutralize each other as to cause the ring *r* to fall away, the attractive force before imparted to the iron by the pole of the magnet M being in this case completely destroyed.

Fig. 24.

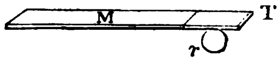
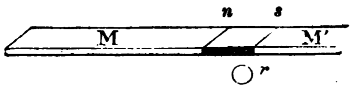


Fig. 25.



MAGNETIC INFLUENCE OR INDUCTION.

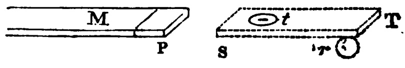
33. We have just seen (32), Experiment 17, that when a piece of soft iron is brought into contact with a magnetic pole, it immediately acquires an attractive power, as if the magnetism of the pole had spread out and pervaded the iron. In fact, if we examine a piece of iron thus circumstanced by means of the magnetoscope (30), we find the same polarity continued throughout the iron; it will every where attract one pole of the magnetoscope, and repulse the opposite pole. If,

however, we separate the iron T, fig. 24, from the magnet, and retain it at a short distance from the magnetic pole, then a new case appears to arise: that portion of the iron next the magnet will have an opposite polarity to that of the pole to which it is opposed; the two magnetic elements (14) resident in the iron will, in fact, become separated; one of them will be sensible at the extremity next the magnet, and the other at its distant extremity,—a result which we might expect to follow from the repulsion of the similar elements and the attraction of the opposite elements (14). This separation of the latent magnetism of the iron into its constituent elements has been termed *magnetic induction.* It is altogether a temporary state or condition of the iron sustained by the influence of a magnetic pole, and vanishes so soon as that influence is withdrawn.

Exp. 18. Place the small magnetoscope (30), fig. 21, on the mass of soft iron T, fig. 24, Experiment 17, in contact with one of the poles of the magnet M, suppose the north pole; it will be found that the similar pole of the magnetoscope will be every where repulsed and thrown up: and if we pass the instrument along the side of the iron, the opposite pole, that is to say, the south pole, will be every where attracted. Hence (30) a north polarity pervades the iron T, and the south polarity or dissimilar element has been neutralized by the opposite element or power of the magnetic pole.

Exp. 19. Let the iron T be now separated from the magnet M by a given distance P S, as shown in the annexed figure 26; then, on applying the magnetoscope *t* to the surface as before,

Fig. 26.



it will be found that one of its poles will be repulsed by the extremity S, and attracted by the distant extremity T: and if we apply a ring of soft iron *r* to the extremity T, it will be held up solely by the influence of the magnet operating

through the iron *r*, at a distance. Let, for example, the opposed pole P be a north pole, then the near end S of the iron will be a south pole, and will repulse the south pole of the magnetoscope, which will be thrown up. On applying the instrument to the distant extremity T, the reverse of this will occur; that extremity will be found to be a north pole, and will repulse the north pole of the magnetoscope, so that the north pole P of the magnet will vanish as it were on the iron, and reappear at its distant extremity; and the iron will, under the influence of the magnetic pole P, become itself a temporary magnet, having its two poles and mean line, as in any other magnet of a permanent kind. A similar result will be arrived at in passing the magnetoscope along the side of the iron, as in the last experiment.

34. It is, however, to be observed, that the position of the mean line will vary with the distance of the iron from the magnetic pole, and will approach the centre of the iron as we increase its distance from the pole, and conversely will approach the near extremity as we decrease its distance from the same pole; so that on making contact with the magnet the mean line vanishes, and the whole mass exhibits the same polarity as the pole of the magnet, resolving itself into the case already illustrated, Exp. 18.

Exp. 20. Place the magnetoscope on the surface of the iron, as in the last experiment, fig. 26, and having applied the iron at a given distance from the magnet, slide the instrument gradually, either towards or from the near end S of the iron, until a point be found in which the needle ceases to be repelled by the polarity of that extremity: if the distance between the iron T and the magnetic pole P be small, that point will not be far from the near extremity S. Let the distance P S between the magnet and the iron be now increased, the neutral point will be found to have receded from the extremity S, and to have approached the centre of the iron.

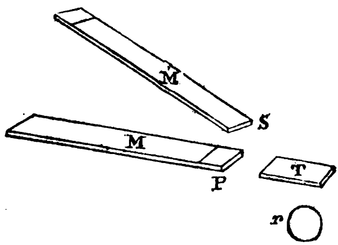
If the distance between the iron and the magnet be suffi-

ciently great, and we allow the magnetoscope to project over the near end S, a second neutral point will be found in the space between the iron and the magnetic pole, on which neither pole of the needle will be repelled.

35. We may perceive by these experiments, that the influence of the pole P has been such as to separate the two magnetic elements resident in the iron, attracting and rendering sensible, in points toward the near extremity S, the element opposite to that of the pole P, and repulsing and rendering sensible the similar element in points more remote and extending to the distant extremity T. The iron has thus become, under the influence of P, a temporary magnet. If therefore we neutralize the polarity of P, by presenting to it the opposite pole of an equal and similar bar, this induced magnetic state of the iron T will immediately vanish.

Exp. 21. Suspend, as shown in the last experiment, fig. 26, one or more rings of steel or soft iron, at the extremity of the iron T, and then bring the opposite pole S of an equal and similar bar M′, fig. 27, gradually over the pole P of the inducing magnet M; the ring *r* will be then observed to fall away from the iron T, by the neutralization of the opposite forces resident in the poles P S of the two magnets M M′; and these actions will all take place at a distance, without any near contact of the respective masses.

Fig. 27.



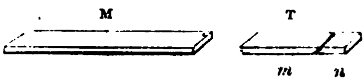
It is desirable in these experiments that the iron should be very soft, and be in no sensible degree magnetic: it should be of the same breadth and depth as the magnet, and may be about one-fourth of the length. Bars about 2 feet long, $1\frac{1}{4}$ inch wide, and $\frac{3}{8}$ths of an inch thick, are well adapted to these

investigations; they may however be successfully pursued with much smaller bars.

36. The two magnetic forces being thus separable by induction, Exp. 19 (33), and made to appear, as it were, in different parts of a mass of iron, it might be inferred, that if we could remove the distant extremity of the iron T, fig. 26, whilst under the influence of the magnet M, we should thereby obtain one of the elements in an insulated state, much in the same way as we obtain the positive or negative force in electricity, under similar circumstances.* Such, however, is not the case: on the removal of a distant portion of the iron, all traces of polarity vanish.

Exp. 22. Let the iron, T, fig. 28, be constructed in two parts *m n*, closely ground together, the part *n* being about 2 inches long, and *m* 3 inches long. Place this compound mass under the influence of the magnet M, as in Exp. 19, so that the extremity *n* may become attractive of a ring of soft steel, and repulse or attract one pole of the magnetoscope (30): fix the iron T and magnet M, and then withdraw the distant portion *n*. The extremity *n* will no longer repulse one of the poles of the magnetoscope, but will operate equally on both, showing that its polarity has vanished; neither will it exhibit any attractive power on soft iron or steel: the induced force has hence disappeared.

Fig. 28.



We may conclude from this experiment, that either both the elements were always present, and had now recombined, or otherwise that the opposite element had been derived from surrounding matter,—a supposition scarcely tenable in the present state of our knowledge of magnetic phenomena. Whatever be the nature of the agency upon which these

* 'Rudimentary Electricity,' Exp. 14, page 15.

curious facts depend, there is every ground for supposing that the two elementary forces (14) never leave the particles of matter with which they are associated. Thus, in the communication of magnetism by the lodestone to hardened steel (16), and from one piece of steel to another without limit (16), neither the lodestone nor the artificial magnet loses any of its inherent power; nothing therefore appears to be communicated; the whole result is entirely a species of molecular excitation, or a calling into sensible activity certain forces already existing in the magnetic substance (33), and which, under ordinary circumstances, remain in a quiescent or neutral state. No means yet devised have ever insulated these forces in such way as to enable us to obtain one of them only, independently of the other. We cannot, for example, produce a magnetic bar having a single pole; for although we touch one extremity of the bar only with one pole of the lodestone (16), still two poles will appear in the bar, although the one induced by the presence of the other may not be so forcible.

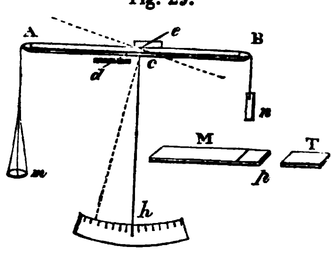
Exp. 23. Magnetize regularly a bar of very highly tempered steel, break it into two parts exactly in its mean line (26) or magnetic centre, on one side of which we have one kind of polarity, and on the opposite side the reverse polarity (26). Examine the fractured ends of each piece by the magnetoscope: two poles will be found to exist in the line of fracture, that is to say, in the points which before appeared neutral. If we again break the two parts each into two other parts, the same result ensues, and so on without limit. The only exception will be, that the magnetic centre and mean line (26) may not fall at the centre of the fractured parts. Such experiments are easily made with bars very highly tempered (87). It appears, therefore, that in every instance of magnetic excitation the two forces are present, and are both developed together.

REACTIVE FORCE OF IRON AND MAGNETS ON EACH OTHER.

37. The influence of a magnetic pole in inducing in a mass of iron a temporary magnetic state, Exp. 19 (33), being such as to cause an opposite or dissimilar polarity to appear at the proximate parts of the iron, and the same kind of polarity in the more remote or distant parts, we should expect to find a given amount of neutralization of the magnetic pole or reactive force apparent, much in the same way as if a second permanent and opposite magnetic pole were opposed to the pole of the inducing magnet (35), Exp. 21, and such is observed to be the case.

Exp. 24. Run a fine needle *d e*, fig. 29, transversely and perpendicularly through the centre of the opposite angle of a light beam of clean-grained deal A B, about 14 inches in length, and one-fourth of an inch square, so as to give the beam a delicate axis of support. Mount this beam on two small cheeks of glass *d e*, supported in any convenient way. Suspend a small cylinder of iron *n* from one of the arms B, by a light silk thread, and counterpoise it by weights placed in a small scale-pan *m*, suspended in a similar way from the opposite arm A: the iron cylinder may be about $1\frac{1}{2}$ inch long and one-fifth of an inch in diameter: it should be carefully constructed of very soft iron. Attached to the centre of the beam under the axis is a light index of reed *c h*, moveable over a graduated arc *h*.

Fig. 29.



The beam being accurately poised, and the index *c h* at zero of the arc, place one of the poles of a powerfully magnetic bar M at such a distance beneath the suspended iron

n, as will incline the beam A B without oversetting the balance, and bring the index into the position of the dotted line, that is, to a certain division of the arc. The beam being thus inclined, oppose to the pole *p* a mass of soft iron T, of equal breadth and thickness to the magnet M. The beam will immediately tend to right itself, and the index will again decline, showing the neutralizing or reactive influence of the iron on the pole of the magnet M.

38. It will be convenient, in experiments of this kind, to place the iron and magnet on a graduated scale resting on a small table, the elevation of which may be varied, so as to measure the distance between the extremities of the magnet and iron, and at the same time, by means of a vertical graduated scale, note the distance between the magnet and suspended iron *n*. (See 'Philosophical Transactions' for 1831, p. 501, Plate XIV.) See also fig. 77 (123.)

Exp. 25. This reactive force of the iron T on the magnet M will be also apparent in placing the iron immediately under the magnetic pole, as at *p*, fig. 29, but it will not be so sensibly indicated as in the last case: it will be also evident in placing the iron over the magnetic pole, immediately between the magnet and suspended iron, in which case, by operating more directly on the nearest points, it is powerfully apparent. The iron has been said, in this case, to screen off or intercept the magnetism of the bar M,—a result commonly attributed to a sort of insulating power or magnetic opacity in the iron, but which evidently arises solely from the annihilation of the attractive force to a greater or less extent (35); the same result being obtained when the iron is placed either beneath or at the extremity of the bar. We have merely to observe in this last case, that the iron must not be so near the suspended cylinder, nor the magnet so near the iron, as would affect the balance, by induction upon the intervening mass (33).

39. The distance within the magnet at which the neu-

tralizing effect of the iron is sensible when placed next its extremity, as in Exp. 21 (37), has no limit, but is felt in every point up to the central parts of the bar in which the least degree of force can be detected.

Exp. 26. This may be easily observed by bringing given points of the bar under the suspended cylinders, and opposing a mass of iron to the magnetic pole at a given distance. The amount of neutralization depends, as may be conceived, on the force induced in the iron, and on its distance from the magnet. Large masses of iron up to a certain limit, and varying with the degree of force in the magnetic bar, have a greater neutralizing influence than smaller masses, and it appears to be of no moment to the experiment whether the iron be opposed to the magnet in the direction of its length, as in fig. 29, or be placed transversely to the pole.

Exp. 27. Repeat the preceding experiment with bars of different degrees of power, and masses of iron varying in dimensions; the respective neutralizing effects will be easily determined.

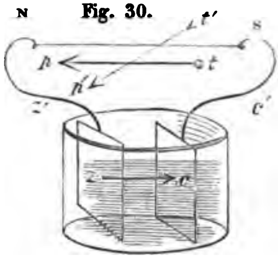
III.

Reciprocal Action of common Magnetism and a Voltaic Current—Electro-magnetic Forces—Magnetic Deflections and Rotations—Electro-magnetic Multiplier—Steel magnetized by Electrical Currents—Electro-magnets and the Laws of the Development of Magnetism by Voltaic Electricity.

40. The next series of phenomena claiming attention, arise out of a property peculiar to natural and artificial magnets, by which they tend, when freely suspended, to arrange themselves in a certain relative position to a wire carrying a current of Voltaic electricity. These phenomena have been hence termed electro-magnetic, and although of sufficient moment and extent to come under a separate and peculiar branch of physical science, yet so far demand a brief notice here, as constituting a very important property of the natural and artificial magnet.

With a view to a clear conception of these reciprocal magnetic and Voltaic actions, it is requisite to understand that two plates of zinc and copper, *z c*, fig. 30, placed near each other in a vessel of dilute acid, and connected by a metallic circuit *c′* S N *z′*, turned or directed in any manner, give rise during the solution of the zinc in the acid to a peculiar electro-chemical action, by which a current of electricity is supposed to flow from the zinc plate *z*, in the direction of the small arrow, through the acid upon the copper plate *c*, and from thence through the metallic circuit *c c′* S N *z′ z*, back again upon the zinc plate *z*: a combination of this kind has been termed a Voltaic circle, and the metallic circuit *c′* S N *z′*, the uniting wire.

Fig. 30.



Exp. 28. This understood, let S N be a perfectly straight portion of this circuit, which, as a standard of reference as to position, we will suppose to be in the direction of the magnetic meridian (7). Let *p t* be a magnetic needle suspended by means of the arrangement, fig. 14 (24), below and parallel to N S; then, directly we complete the communications N *z' z*—S *c' c* with the zinc and copper plates *z c*, the needle *p t* varies from the meridian, and tends to place itself across the wire N S, and in such way that whichever pole of the needle is next the copper plate *c*, that pole moves to the right hand or towards the east. If therefore, as in fig. 30, the current flow over the needle from *c* to *z* through the wire S N from south to north, and the observer be looking over the wire in the same direction—then the south pole *t*, next the copper plate *c*, turns to his right hand or to the east, and the north pole *p*, to his left hand or west. If we suppose the position of the plates *c* and *z* to be changed, and the direction of the current reversed, by connecting the extremity N with *c*, and the extremity S with *z*, so as to cause the current to flow from north to south, then these deflections are also reversed. The south pole *t* now goes to the left hand, and the north pole *p* to the right hand—that is to say, the north pole *p*, being now next the copper plate, goes to the right hand.

Exp. 29. Place the needle above and parallel to the wire S N, then the reverse of all the former deflections will be obtained; whichever pole of the needle is now next the copper plate, that pole moves to the left hand or west. When the current, therefore, flows from south to north, the south pole *t*, which before went to the right hand or east, now goes to the left hand or west, whilst the north pole turns to the right hand: if we reverse the current, and cause it to flow from north to south, as in the last experiment, then these deflections are again reversed; the north pole of the needle, being now next the copper plate of the battery, goes to the left hand.

41. The following Table I. comprises, under a perspicuous form, these several deflections, together with the relative positions of the needle and direction of the current:

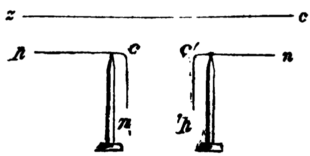
TABLE I.

Wire over the Needle.		Wire under the Needle.	
Direction of current.	Deflections.	Direction of current.	Deflections.
(*a*) South to North	N. Pole to the left. S. Pole to the right.	(*c*) South to North	N. Pole to the right. S. Pole to the left.
(*b*) North to South	N. Pole to the right. S. Pole to the left.	(*d*) North to South	N. Pole to the left. S. Pole to the right.

42. That these deflections arise from a distinct and independent action of the current on each pole of the needle at the same instant, is evident from the following experiment:

Exp. 30. Let $p\,c\,n$ and $n'\,c'\,p'$, fig. 31, be two light magnetic bars, bent so as to place one half the bar $p\,c$ at right angles to the other half $n\,c$; balance these magnets on fine centres $c\,c'$, immediately under a wire $c\,z$, to be connected with the zinc and copper plates of the Voltaic circle: take $c\,z$ in the direction of the magnetic meridian as before, and suppose the poles $p\,n'$ of the magnets in the same straight line $p\,c\,c'\,n'$. We may, in this arrangement, take the distant vertical poles $n\,p'$ of these bars to be without the limit of the influence of any current passing through $c\,z$: connect the wire $z\,c$ at points $z\,c$, with the zinc and copper plates of the Voltaic circle, fig. 30; both the magnets will be moved, and in opposite directions, as specified in the above Table.

Fig. 31.



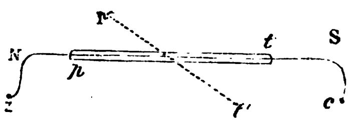
It may be seen, by reference to this Table, that the same deflections are produced by a current flowing over the needle from south to north (*a*) as by a current flowing under the needle from north to south (*d*); and, reciprocally, a cur-

rent flowing under the needle from south to north (c) produces the same deflections as in flowing over the needle from north to south (b). Hence, if in the last experiment, fig. 31, one of the bars, $p'\ c'\ n'$, be raised above and parallel to the wire $c\ z$, whilst the other, $p\ c\ n$, remains beneath it, then, on transmitting a current through the wire, both the bars move to the same side, that is, are deflected in the same direction. It is not requisite, in these experiments, to place the bars or needle immediately over or under the wire S N; it is sufficient that the needle be near and parallel to the wire, either above or below it.

43. If the needle be immediately in the plane of the uniting wire on either side of it, no motion is obtained in that plane; but if it be suspended in a vertical plane, on a horizontal axis, by means of the apparatus described, fig. 14 (24), so as to admit of a deflection of inclination, then it tends to place itself across the wire as before. If the needle be on the east side of the uniting wire, that is, on the right hand, taking the current and direction as at first, then the south pole next the copper side of the battery dips below the horizontal plane, and the north pole next the zinc plate rises. If the current be reversed, the deflectious are also reversed. If the needle be placed on the left hand or west side of the uniting wire, then the south pole next the copper plate rises, and the opposite north pole dips: by reversing the direction of the current, these deflections are again reversed.

Exp. 31. Let the horizontal bar $a\ b$, fig. 14 (24), be placed at one side and parallel to the wire S N, fig. 30, as indicated in the annexed fig. 32, in which S N is the uniting wire placed in the meridian S N, and $p\ t$ the bar balanced on the horizontal pivot, fig. 14: complete the connections with the Voltaic plates, fig. 30, the extremity S being connected with the

Fig. 32.

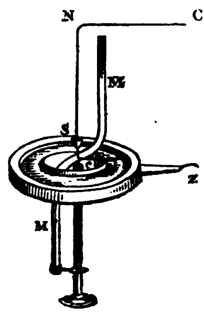


copper plate *c*, and the extremity N with the zinc plate *z*; then the pole *t*, nearest the copper plate *c*, dips below the wire N S if the bar be on the east side of the wire, and rises above it if on the west side.

44. It is apparent, from the successive directions of the bar as it becomes placed above, at the sides, or below the wire S N, that the force affecting the magnet is a force transverse to the pole of the bar, by which, if the bar had complete freedom of motion in every direction, the poles would actually turn round the wire, but in different directions; and, conversely, supposing the bar fixed and the wire S N carrying the current free to move, then those parts of the wire parallel to the magnet would rotate about the magnetic poles in opposite directions, in a similar way. If both are supposed free to move in any direction, then the wire and magnet would turn round each other; and such is really found to happen, giving rise to a very beautiful and most important series of electro-magnetic actions.

Exp. 32. Let a magnetic bar M M′, fig. 33, be bent so as to produce a short oblique portion at the middle of the bar, with two vertical arms M M′; poise it on a fine central point *c*, and let a wire N S be placed near and parallel to one of the arms, M. Then, supposing a descending current to flow from the copper plate *c*, fig. 30 (40), through the wire in the direction N S upon the zinc plate Z, the magnet M revolves about the wire N S, upon the central point *c*; and if the north pole of the bar be uppermost, the motion will be direct, or from the left hand to the right.

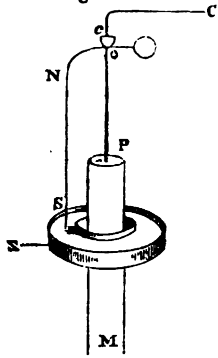
Fig. 33.



Exp. 33. Conversely, if the magnet M be fixed as in the annexed fig. 34, and the wire N S be moveable on a fine centre O, then, on transmitting the current as before,

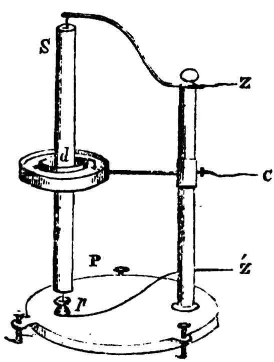
through the wire N S, it immediately revolves about the pole P of the magnet, with a direct screw-motion, supposing the current to descend the wire, and the pole P to be a north pole. To enable these motions to go on without disturbing the progress of the current and the connections with the Voltaic plates, the moveable parts dip into small cups and cisterns containing mercury, and with which the plates of the Voltaic circle, fig. 30, communicate, as indicated in the figures.

Fig. 34.



45. The tangential or transverse force, by which a magnetic pole is caused to revolve about a wire transmitting a current of Voltaic electricity, is equally apparent when the magnetic bar itself becomes the conjunctive wire of the battery; so that an electrical current flowing over or through a magnetic bar from one of its poles to the equator, or from the equator to either of the poles, causes such a bar to revolve upon its axis, the requisite mechanical arrangements for motion being complete.

Fig. 35.



Exp. 34. Let a magnetic bar S P, fig. 35, be mounted vertically between two delicate centres: the bar may be about 18 inches in length, 1 inch wide, and $\frac{1}{4}$ of an inch thick. Let an electrical current (40) be caused to flow from either of the poles P S to the equator *d*, or from *d* to either of the poles P; the bar

will immediately revolve upon its axis P S, the direction of the motion being such that, supposing the bar to rest upon its north pole P, the centre *d* being in communication with the copper plate of the battery C, and either or both of the poles P S in communication with the zinc plate Z, electrical currents will flow from the equator *d* to the poles (40), and the bar will revolve from left to right, as in the motion of the hands of a watch, or a common right-handed screw. By reversing the communication with the Voltaic plates, that is, placing the poles P S in connection with the copper plate, and the centre *d* with the zinc plate, the electrical current will flow from the poles to the equator *d*. In this case, the direction of the motion will be the reverse of the former; it will be from right to left, or backward, as it were.

Exp. 35. If the position of the magnet be changed, that is, if we place it to rest with its south pole below, then, the communication with the Voltaic circle remaining as in the first instance, we also reverse the motion. If now the communications be changed as in the last instance, we again reverse the motion, and obtain, as at first, a motion from left to right.

To facilitate the passing of the electrical current over the magnet, the bar is supported between fine centres P S by a light vertical column fixed on a firm base; a small ring or cistern of mercury *d*, also supported from the vertical column, surrounds the equator of the bar: the bar turns within this, and it is connected with the mercury in turning by a small bent wire dipping into the cistern: the lower centre P turns upon an agate contained in a small cup at P, connected with the point Z′: this cup contains a small globule of mercury, to keep up the metallic connection with the magnet: there is a similar globule in a small cavity at the upper end of the bar for the centre S: this upper centre is supported by a wire extending from the head of the pillar Z Z′. It is here evident, that in connecting the points C Z or C Z′ with the

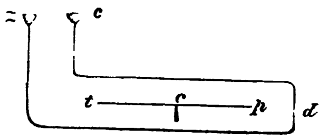
plates of the Voltaic circle (40), an electrical current will flow between these points through c *d* s z, or c *d p* z′, the direction depending on the respective connections with the zinc or copper plate of the circle (40).

A recollection of the relative direction of the motions we have been describing will be facilitated by keeping in mind the following simple formula: a descending current moves a north pole to the right hand, or will give rise to a direct screw-motion: from this simple fact all other relative motions are easily determined.

46. The reciprocal action of a magnetic needle and uniting wire (40), together with the series of deflections in given directions shown in Table I. (41), have led to the invention of a very important magnetical instrument, termed the Electro-magnetic Multiplier, or Galvanometer, by which extremely small magnetic and electro-magnetic forces may be detected and measured.

It will be apparent by inspection of Table I., as already observed (42), that a current flowing both above and below a needle in opposite directions, deflects the needle in the same direction: hence it follows that if a magnetic needle *p t*, fig. 36, be suspended on a delicate centre *c*, within the bite of a returning wire *z d c*, and the extremities *z c* of the wire connected with the zinc and copper plates of the Voltaic circle by means of two little cups containing mercury, then a current will flow longitudinally round the needle, both above and below it, and in opposite directions; that is to say, in the direction *c d* above the needle, and in the direction *d z* under it: the effect of this will be to deflect the needle with twice the power by which it would be deflected with a single current only, as in fig. 30 (40).

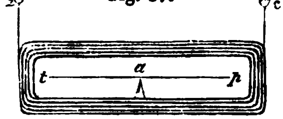
Fig. 36.



If we imagine the wire *z d c* to be several times turned lon-

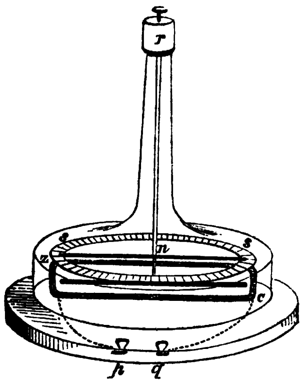
gitudinally about the needle, as in the annexed fig. 37, then the effect would be still further increased; it would, in fact, become multiplied in proportion to the number of turns of the wire, which would represent so many additional currents. It

Fig. 37.



is only requisite to cover the wire with silk thread or some other imperfect or non-conducting matter, so as to avoid metallic communication between the coils, and oblige the current to traverse the whole length of the wire. This is the principle upon which the electro-magnetic multiplier rests, and the delicacy of the effect is such that the needle will become deflected by the immersion of two pieces of zinc and platinum wire less than $\frac{1}{8}$th of an inch long and $\frac{1}{50}$th of an inch in diameter, in water slightly acidulated. The annexed fig. 38 represents this instrument under one of its most perfect and delicate forms. Two magnetic needles with their poles reversed to each other are fixed on a central rigid axis, so as to neutralize the directive power of the needles and render the system astatic (29) or nearly so, merely allowing a sufficient force to bring the whole into the meridian. This system is suspended by two parallel threads of unspun silk *r n*, one of the needles being within a rectangular coil of wire *z d c*, and the other needle immediately without it, and over the upper part of the coil. The wire *z c* is covered with silk thread, so that the coils may not have metallic communication, and the extremities *p q* are brought out near each other, and terminate in small cups *p q*, con-

Fig. 38.



taining a little mercury, for the better convenience of communicating a current to the coil from any given source. The coils are separated a little near the centre, to allow the axis of the astatic system of the two needles to pass through them.

The slightest current transmitted through the coil from *p* to *q*, or *q* to *p*, causes the needles to deviate from their constant position: both the needles, as is evident, will be impelled in the same direction; the lower needle being in the position just described, figs. 36 and 37, whilst the upper needle, its poles being reversed, is impelled in the same direction by the upper side of the coil (41).

The threads of the double or bifilar suspension *r n*, in tending to cross each other as the needles turn, give rise to a reactive force which may be set against the deflective force employed to measure it: for this purpose a graduated circle *s s* is fixed under or round the upper needle, so that the angle of deflection may be accurately estimated.* If the earth's directive force be completely neutralized by the reversed positions of the needles, then this would be the only force opposed to the deflective force; if not, then it becomes mixed with the little directive power left in the system, but which is generally so small as not to be of much moment.

The instrument is set upon a convenient stand, and may be enclosed within a glass shade; the bifilar suspension being sustained within a tube of glass.

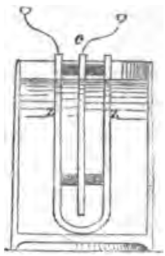
Various forms of the electro-magnetic multiplier have been devised: several have a single needle only, as in the arrangement, fig. 37, which for all ordinary purposes answers extremely well, and is in some particular instances to be preferred.

47. The simple Voltaic circle, described fig. 30 (40), has been hitherto the only kind of combination referred to, on account of its simplicity; it may, however, be proper to observe that we possess better and more certain forms of this valuable

* Phil. Trans. for 1836, Part II. page 417.

instrument of research. The Voltaic circle, invented by Mr. Smee, and termed Smee's battery, is well adapted, and certainly the most convenient, for ordinary purposes. In this arrangement a silver plate *c*, fig. 39, coated with platinum, and termed platinized silver, is substituted for the copper plate in the original circle (40); this is enclosed between a double zinc plate, or between two zinc plates z z, held firmly against a centre block of wood at the upper edges of the plates by a clamp and binding-screw, so that they have metallic communication, and act together as a single plate. The platinized silver plate is prevented from touching the zinc in any part by intermediate non-conducting matter. The current in this arrangement flows as before; that is to say, the platinized silver plate has the same relation to the zinc plate in this circle as the copper plate in the original circle, fig. 30 (40): the difference is merely in the substance, arrangement, and position.

Fig. 39.



We are indebted to Mr. Grove for the most powerful Voltaic combination as yet produced: the metals employed are platinum foil and zinc, coated with mercury: the exciting liquids are concentrated nitric and dilute sulphuric acid.

It may be as well to observe, that the experiments hitherto described have reference to a single combination only; that is to say, a single Voltaic circle with two plates, or acting as two plates only, and not to a series of such plates in cells, as in the ordinary compound batteries: in these the course of the current through the wires is not the same as in a battery with a single pair.

STEEL MAGNETIZED BY THE ELECTRICAL CURRENT.

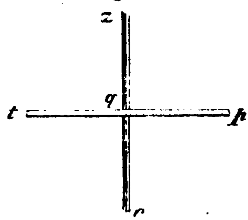
48. One of the many important results of these discoveries is the means of imparting a high degree of magnetism to iron

and steel, and to so great an extent as to give a soft iron rod a lifting power of more than a ton.

We have seen (40) that the electrical and magnetic forces are so related that the one is exerted at right angles to the other; thus (Exp. 28) a magnetic needle tends to stand directly across the conjunction wire. We derive from this elementary principle a means of disturbing the latent magnetic forces resident in magnetic substances, by which these forces become separated, and the body rendered magnetic, precisely in the same way as effected by the contact of an ordinary magnet (20).

Exp. 36. Place a perfectly neutral bar of hard steel *p t*, fig. 40, across a metallic wire *c z*, uniting the plates of a simple Voltaic circle (47), and as a standard of reference as to direction and position, let the uniting wire *c z* be in the line of the magnetic meridian, *c* being its south, and *z* its north extremity. Under these conditions, draw the bar *p t* forward and back several times across the wire *c z*, from end to end, finally stopping in the centre *q*: on removal, the bar will be found to have acquired a strong polarity. If the current be passing from *c* to *z*, that is, from south to north, the wire being in this case under the bar, then the east or right-hand extremity *p* will have become a north pole, and the left hand or west extremity *t* a south pole, which is precisely what would happen from the experimental facts already given (41), and from which it must also follow, that by reversing the direction of the current on placing the bar under the needle, the resulting polarities would be also reversed.

Fig. 40.



Exp. 37. Place the bar *t p* under the wire *c z*, all other things being the same, and repeat the process of magnetizing as in the last experiment; on removal, the west

or left-hand extremity will have become a north pole, and the east or right-hand extremity a south pole. By reversing the current in either of these cases, Experiments 36 and 37, so as to cause it to flow in the direction of *z c*, or from north to south,—we again reverse the polarities of each, and may hence obtain the same polarities whether the bar *p t* be placed over or under the wire *c z*; that is to say, a current flowing from *c* to *z* under the bar will give rise to the same polarities as in flowing from *z* to *c* *over* the bar.

49. As it is important to remember these relative directions and polarities, it may be as well to reduce them to a simple tabular form.

TABLE II.—*Showing the relative Polarities induced in a Bar of Steel by the influence of an Electrical Current, the Bar being at Right Angles to the wire, fig.* 40.

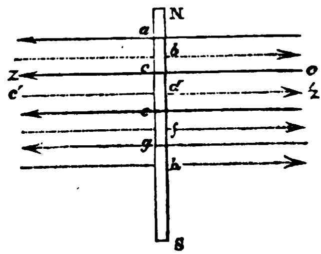
Current and Connecting Wire *over* the Bar.			
	Direction of the current.	Relative position of the N. and S. Poles.	
Bar under wire.	(*a*) South to North	Positive Pole determined to the left Negative Pole determined to the right	Case 1.
	(*b*) North to South	Positive Pole determined to the right Negative Pole determined to the left	
Current and Connecting Wire *under* the Bar.			
Bar over wire.	(*c*) South to North	Positive Pole determined to the right Negative Pole determined to the left	Case 2.
	(*d*) North to South	Positive Pole determined to the left Negative Pole determined to the right	

We see here that similar polarities may be obtained with the bar either above or below the uniting wire, provided the currents be reversed as in Experiments (*a*) and (*d*), and that in both cases the results are virtually the same as already arrived at by means of the magnetic needle (41), Table I.

50. If we suppose a steel bar N S, fig. 41, crossed by several wires *a b c d*, some above and some beneath the

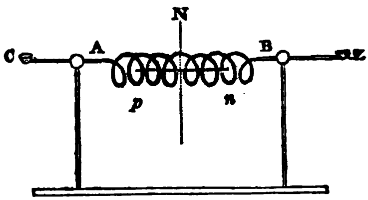
bar, and currents passing through the wires over the bar, all in the same direction *c z*, and through those under the bar, all in the reverse direction, *c′ z′*,—such currents would all conspire to determine the north polar element in one direction, and the south polar element in the opposite direction (41), Table I., and the bar would be at once rendered magnetic. If the wires were sufficiently numerous to cross the bar on each point *a b c d*, &c., from end to end, every point would be acted on, and the resulting magnetic state become thereby powerfully developed.

Fig. 41.



Exp. 38. Let a long piece of copper wire be wound round a piece of glass tube of about ½ an inch or less in diameter, and from 6 to 10 inches in length, so as to produce a helix or spiral, A B, fig. 42, and mount this spiral between two vertical supports as represented in the figure. Place a perfectly neutral piece of hard steel wire *p n*, of about $\frac{1}{10}$th of an inch in diameter, or a large sewing needle within the helix, and connect the extremities A B with the zinc and copper plates of the Voltaic circle, fig. 39, the steel *p n* will become immediately magnetic; in fact, each turn of the spiral causes electrical currents to flow in reverse directions above and below the steel, as just described, fig. 41. If the coils of the spiral be numerous and close, they may be regarded as parallel circles standing at right angles to the direction of

Fig. 42.



the enclosed wire, and with which the axis of the helix may be made to coincide. The effect of a helix of this kind on a fine magnetic needle placed within it, is so powerful, that with a strong Voltaic current the needle is frequently caught up and retained on the axis of the spiral, as if liberated from the trammels of gravity.

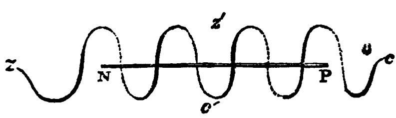
51. The kind of polarity given to steel or iron thus circumstanced will, as may be inferred (46), depend on the direction of the current with reference to the axis of the helix, and this again will depend on the connections with the plates of the Voltaic circle and the direction in which the helix is turned. Now, the spiral may evidently be turned either direct, as in the threads of a common cork-screw, forming what is termed a right-handed helix, as in the annexed figure 43, or they may be turned in the reverse direction, in which case we have a left-handed helix, as in the annexed figure 44.

Fig. 43.

Fig. 44.

Exp. 39. If we suppose the helix to be a reverse or left-handed helix, as in the annexed figure 45, the current flowing from *c* to *z*, round a small cylindrical steel needle or wire P N, and the coils standing in the direction of the magnetic meridian *c′ z′*, so that the current may flow under the wire in the direction *c′ z′*, from south to north, as indicated by the dotted lines, and over the needle in direction *z′ c′*, from north to south, as indicated by the full lines, then any one of the coils *c′ z′* under the wire would fulfil the conditions of Experiment 36, and with the wire itself be faithfully represented in fig. 38. In this case, as may be seen by Table II. (49), case 2 (*c*), and case 1 (*b*), the positive pole P will be determined to the

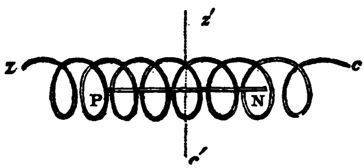
Fig. 45.



right hand, and the extremity P, of the wire next the copper plate *c*, will be a north pole: by similar reasons the opposite extremity N will be a south pole, and next the zinc plate of the battery.

Exp. 40. If we take a direct or right-handed helix and an enclosed wire P N, as in the annexed figure 46, and transmit the current as before from *c* to *z*, then the reverse of all this occurs; the currents flow *under* the wire from north to south in direction *z′ c′*, and over the wire from south to north in direction *c′ z′*.

Fig. 46.



Under these conditions by Table II. (49), case 2 (*d*), and case 1 (*a*), the positive pole P is determined to the left hand, so that the extremity P of the steel cylinder P N next the zinc plate becomes a north pole, and, by similar reasoning, the opposite extremity next the copper plate *c*, a south pole. Supposing the current to be reversed and to pass through a direct helix from left to right, as from *c* to *z*, fig. 42, the copper plate of the battery being to the left hand, and which is the ordinary form of the experiment, the north pole will be always determined next the zinc plate, that is, to the right hand.

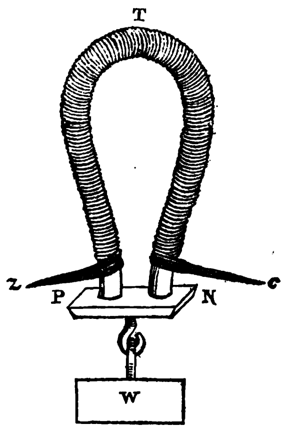
52. It will be useful to the student to remember as a general fact, that supposing, fig. 42, the observer to be facing the north, N, and the helix A B placed transversely before him so that its axis may lie east and west, then if the current be *descending* the coils of the spiral directly before him, the north pole is determined to the right hand, and the south pole to the left. Reciprocally, if the current be *ascending* the coils of the spiral directly before him, then the south pole is determined to his right hand, and the north pole to the left. Hence, with a direct helix, the north pole will be always found

next the zinc plate, and with a left helix next the copper plate, as may be easily seen by inspecting figs. 43 and 44, the direction of the currents being either from left to right, or right to left.

53. The magnetic power developed in soft iron closely surrounded by heliacal coils transmitting electrical currents all in the same direction is so great, that a curved iron rod, during the action of the battery, may be caused to sustain an enormous weight. The usual force of the experiment is as follows.

Exp. 41. A cylindrical bolt of soft iron P T N, fig. 47, about an inch or more in diameter, and from 30 to 40 inches long, is bent into the horse-shoe form, as indicated in the figure. It is then surrounded by several long coils of copper wire *z* T *c*, covered with silk or other insulating thread, so as to interrupt all metallic communication or coil with the other; one set of coils is superposed on another, and all the ends of the wires P N on each side united into common terminations *z c*, to be connected with the Grove's battery (47).

Fig. 47.



If when the currents are passing through the coils we apply a soft iron keeper (10) P N, and cross the projecting poles, it will be held fast with an enormous force, so that several hundred weight, W, may be suspended without breaking the contact. An electro-magnet of this kind may become so powerful as to support upwards of 2 tons.

IV.

Magnetism considered as a Universal Agency—Experiments of Coulombe and Becquerel—Arago's Researches—Influence of Metallic and other Substances on the Magnetic Needle—Faraday's Researches—Magneto-Electricity—Thermo-Magnetism—Supposed Magnetism of Light—Faraday's Discovery of a new Magnetic Condition of Bodies—Dia-Magnetism—General Relation of Magnetic Agency to common Matter.

54. We have seen (32) that magnetic substances are said to attract or are attracted by either pole of the magnet. Non-magnetic substances neither attract nor are attracted by the magnet. Magnetic substances are said to have polarity when they have directive force (7), in which case they attract one pole of a magnet and repel the other (30).

Iron being, with rare exceptions, the only substance in which magnetic properties are powerfully apparent, almost every kind of matter was for a long time considered as non-magnetic; and hence arose an arbitrary classification, assembling the few substances susceptible, together with iron, of being attracted by the magnet, under the head of magnetic bodies, other substances being classified as non-magnetic bodies. It has, however, been made a matter of some question how far all bodies are not to be considered as magnetic bodies, a conclusion which has received very considerable support, by the many brilliant discoveries of modern times in this department of science.

Iron is undoubtedly, of all substances, the most universal and powerful as a magnetic body; and when we consider its great dispersion and admixture in a greater or less degree with other substances, there are certainly some grounds for inferring that the attraction of many bodies for the magnet may depend on the small quantity of iron they contain: the many experiments, however, made on a large class of bodies essentially differing in their composition, and in several of

which the presence of iron could not be well imagined, necessarily led to the conclusion, that some other bodies at least, besides iron, must be considered as magnetic substances.

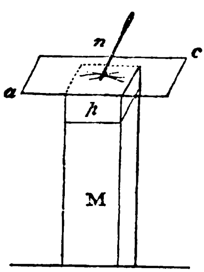
The metal next to iron, which appears to afford the most decided evidence of pure magnetic development, is nickel, which not only attracts and is attracted by the magnet, but is further capable of retaining a distinct polarity. M. Biot determined by a well-executed experiment the comparative directive power of a magnetic needle of pure nickel, and a steel needle of exactly the same dimensions, and found the directive force of the needle of nickel about one-third that of the steel: these needles were 8 inches long, and $\frac{2}{10}$ths of an inch wide, and weighed about 5 grains. The nickel had been carefully purified by M. Thenard.

Mr. Cavallo found that hammered brass also acquired by hammering a great amount of magnetic force, although every care was taken to free the brass from the presence of iron. This philosopher further found, that several metals were also attracted by the magnet. Rhodium, iridium, and antimony, when heated, also evinced this property. Many non-metallic minerals and earths have been found attractive of the magnet, more especially after being exposed to the action of fire.

55. We are indebted to Professor Wheatstone for a delicate and very elegant means of observing such magnetic forces.

Exp. 42. If a fine short sewing needle, *n*, fig 48, the eye end being broken off, rest upon its point *p*, on the polar surface *p* of a very powerful magnet M, it will generally take a position inclined to the surface; but a locality may generally be found, in which the needle will stand nearly vertical: this point may be ascertained by placing a piece of unglazed

Fig. 4

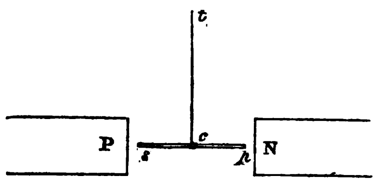


paper *a c* between the needle and point and the steel, and

moving it about until the vertical position of the needle is obtained. If we elevate the paper and needle above the magnet to the greatest distance at which the needle will remain vertical, it becomes to the last degree sensitive of magnetic force, so that by bringing such specimens of the metals we have named, as have the least magnetic power, or containing iron, near the upper extremity of the needle, the needle will be observed to incline and sway about as it were on its point under their influence. The magnetism of nickel, cobalt, rhodium, iridium, hammered brass, and other substances, easily becomes apparent in this way.

56. About the year 1802, Coulombe endeavoured to determine the question of a 'universal magnetism,' by delicately suspending fine needles of various substances between the poles of opposed compound magnets (19), and causing them to oscillate, first, beyond the influence of the magnetic poles, and then immediately between them: the result, as stated by Coulombe, was, that the time of the oscillations became sensibly decreased by the influence of the magnetic poles, and all the substances tried finally settled in the direction of the poles. The annexed figure, 49, represents the form of Coulombe's celebrated experiment; in which P N are the poles of two powerful compound magnets (19), *p s* a small needle of any given substance, about $\frac{4}{10}$ths of an inch long and $\frac{1}{50}$th of an inch thick, suspended between the magnets by a silk fibre *t c*, attached to a small paper ring *c*, in which the needle *p s* was allowed to rest: the needle *p s*, and the poles P N, were covered by a glass receiver to shield the needle from the air; by raising the rod at *t*, through the neck of the receiver, and to which the suspension thread *t c*, and needle *p s*, was attached, it became easy to place the needle, when required, beyond the influence of the magnetic poles. It

Fig. 49.



appeared from these results, that all bodies either contained indefinitely small quantities of iron, or were otherwise susceptible of ordinary magnetic influence, or finally, that, as suggested by M. Biot, the phenomena depend on some force in nature not hitherto known.

57. With a view of detecting the presence of extremely small portions of iron in various bodies, Coulombe resorted to the method of oscillation: having determined the accelerating force of a known mechanical admixture of iron with a given substance, he found that the action of the poles of the magnet was proportionate to the quantity of iron the admixture contained; and that the presence of any quantity of iron, however small, might be thus determined. M. Hauy sought to render this method still more sensible, by deflecting a delicately suspended needle from the meridian by means of a magnetic bar brought within such a distance of the needle, and in the same right line, as would cause the needle to stand nearly perpendicular to the bar, that is, east and west. A needle thus circumstanced is so sensible of magnetic force, that a very feeble magnetic action exerted on it by another body will cause it to turn on its centre of suspension. M. Hauy called this the process of 'double magnetism.'

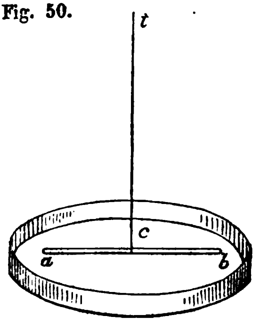
Following out this process, Becquerel, finding that a needle of soft iron might be substituted for the magnetic needle employed by M. Hauy, proceeded to submit to experiment several oxides of iron, which he enclosed in a thin paper case, suspended in various positions at a given distance from the pole of a common magnetic bar; and he found in certain instances, with an admixture of the second and third oxide of iron, that the paper case, instead of taking the line of the pole of the bar, as would be the result with a needle of soft iron, and with the magnet placed beyond it in the same given position, that the case stood at right angles to the line of the poles; from which he inferred that the line of magnetism was transverse to the direction of the poles. On repeating Coulombe's previous experiment, fig. 49 (56), with needles of

white wood and gum lac suspended very near the magnets, but *above* the interval between the poles, he obtained a similar result; the needles, instead of settling in the line of the poles as observed by Coulombe, stood transverse to that line.

58. About the year 1829, M. Arago made very considerable advances in this interesting physical question, by one of those happy perceptions peculiar to great philosophical minds. M. Arago thought of observing the oscillations of a magnetic needle (6), (21), when placed in the vicinity of various substances, so as to detect thereby any force which such substances might exert on it; and he arrived at this remarkable fact—that the influence of substances generally on a vibrating magnetic bar was such as to bring the needle more or less rapidly to rest, by diminishing the amplitude of the oscillations without at all affecting the time in which an oscillation was performed. Metallic substances were found to have the greatest influence on the needle. They all brought the needle to rest more or less rapidly.

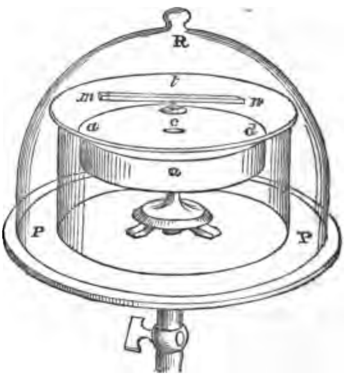
Exp. 43. A small magnetic bar *a b*, fig. 50, suspended by a delicate silk fibre *t c*, within a ring of copper *a c b*, is reduced rapidly to rest on being allowed to vibrate freely across the meridian: *e. g.* a small bar *a b*, about $4\frac{1}{2}$ inches long, $\frac{3}{10}$ths of an inch wide, and $\frac{1}{10}$th thick, was suspended by a fine fibre within a copper ring, about $\frac{1}{8}$th of an inch thick, and an inch deep; the whole was covered by a glass receiver, and the air removed by an air-pump. The bar being drawn aside 45 degrees from the meridian, was allowed to vibrate, and the number of vibrations taken between 45 degrees and 10 degrees. The same being determined when the copper ring was removed, it was found, that in free space the bar performed 420 oscillations

Fig. 50.



before it reached an arc of 10 degrees; whereas when surrounded by the copper ring, with the poles very near the inner surface, only 14 oscillations were performed before the bar oscillated in an arc of 10 degrees; thereby showing the great influence of the metal. In a ring of wood, the oscillations were reduced from 420 to about 300.* This force of metallic bodies on the magnetic needle is so great, that plates of copper and other metals made to revolve rapidly in a horizontal plane, and immediately under a suspended magnetic bar, drag the needle round, and finally set it in rapid motion,—a result which invariably ensues with the bodies completely sheltered from currents of air, and placed under glass screens in the best vacuum which can be produced by a common air-pump. There are several methods of exhibiting this curious fact: a plate of copper or some other metal is set in rapid movement under a magnetic needle, or conversely a magnetic bar is rotated under metallic plates lightly suspended. The rotation may be produced and continued either by a train of wheels and a descending weight, or otherwise by a powerful initial impulse, as in the method of spinning a common humming-top. The following Experiments, taken from the author's papers in the 'Philosophical Transactions' for 1831, are perhaps as perfect as any yet obtained.

Fig. 51.



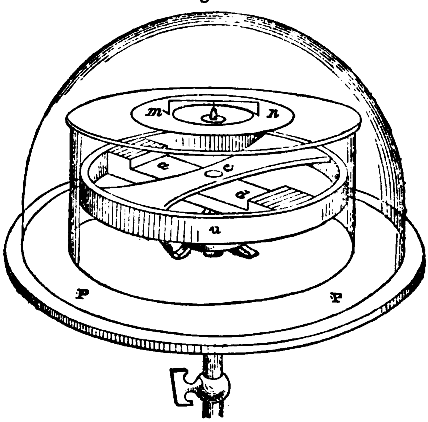
Exp. 44. A plate of copper *a d*, about 5 or 6 inches in diameter and $\frac{1}{8}$th of an inch in thickness, is soldered to a ring of lead *a u d*, about 1 inch deep, turned true in a lathe, and delicately poised

* Harris, 'Philosophical Transactions' for 1831, Part I.

on a point *c*, resting on an agate centre; a screen of flat glass *a t d* is placed over the copper disc, and a magnetic bar *m n* poised on a fine centre is placed centrally on the screen: a silk line having been wound many times round the ring of lead *u*, previously to covering the disc, is attached to a train of wheels, and the line run rapidly off the circumference *a u d*; the whole is by this contrivance set into a smooth and very rapid motion of from 700 to 800 rotations in a minute, which will continue for a considerable time with a slow retardation: when the metal has been thus set in motion, and the bodies are effectually screened from each other in the way just stated, if the centre *c* be previously secured to the plate of an air-pump P P, we may cover the whole with a glass receiver P R P, and withdraw the air; in a short time the magnetic bar *m n* will be observed to spin round with immense rapidity.

Exp. 45. For exhibiting the rotation of a metallic plate by the influence of a magnet, we may employ a hardened and magnetized circular steel plate mounted on a ring of lead, as in the former case, or a small set of magnetic bars *ad*, fig. 52, set and poised in a ring of lead *u*, and mounted on a centre *c*, as before: the plate of copper *m n*, or other metal, is poised on a fine point, and placed immediately over this on a glass screen, rapid motion being imparted to the magnetic plate

Fig. 52.



or magnet *a d*, as before; the copper plate above begins to rotate, and finally revolves rapidly with the magnet.

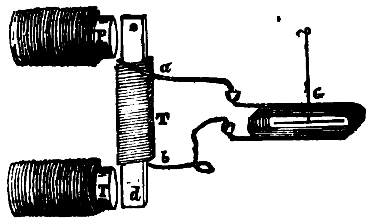
59. When these novel effects were first obtained, they were supposed to arise from the latent magnetism of matter generally, by which certain small temporary forces were induced in bodies in the common way of ordinary magnetic induction (33), and that hence we had additional evidence of a universal magnetism. Arago, however, before attempting any explanation of the cause of the phenomena, sought with his usual penetration to resolve the force in operation into certain relative components, and he found amongst these a vertical repulsive force by which a long needle, suspended and poised over the revolving disc from the arm of a delicate balance, became thrown up: a second component consisted of a horizontal force by which the bar over the disc rotated; and a third was observed to act in the direction of the radius of the disc, so that a dipping-needle or needles of inclination (29) became in certain points repulsed from the centre of the disc, in other points drawn toward it. Taking these phenomena into consideration, together with the total absence of all sensible attraction between the magnetic needle and the copper plate when at rest, Arago concluded that the force in operation was not an ordinary magnetic force, but arose out of some peculiar and unknown agency to be yet investigated: the important fact, that only the amplitude, not the time of the vibrations of the magnetic needle, is affected by the presence of a metallic or other substance, would go far in support of this opinion, since in every case in which an oscillating needle is exposed to the action of a magnetic substance, the time of its vibrations is changed.

60. About the period of these researches, Faraday, considering that as magnetism could be derived from the influence of ordinary electrical currents, the converse of this proposition should be also true, and that magnetism should be producible by Voltaic currents, sought by the operation of powerful magnets on helices of wire (51) to develop currents of elec-

tricity throughout the wire; and he succeeded in obtaining such currents for a small portion of time sufficiently strong to affect the electro-magnetic multiplier (46), so strong as even to produce the ordinary electrical spark, and in the following way.

Exp. 46. A cylinder of pasteboard T, fig. 53, was surrounded by several superposed helices of copper wire *a b*, about $\frac{1}{20}$th of an inch in diameter, and cut off from each other by silk or some bad-conducting matter; all the extremities were collected at each end, *a* and *b*, and connected with an electro-magnetic multiplier G; a cylinder *c d* of very soft iron was placed within the pasteboard case T, that is, within the spirals *a b*, and then the extremities *c d* of the cylinder were brought into contact with the opposite poles P T of two powerful magnetic bars, or an electro-horse-shoe magnet (53). A brief but decided electrical current rushed through the spirals, and the needle of the galvanometer became deflected in a given direction: here the action apparently ceased, but, on breaking the contact with the magnetic bars, an opposite rush of electricity was induced in the wire, and the needle became deflected in the reverse direction. This effect, but in a less degree, was found to ensue by contact with the helix only, without the iron cylinder: in this case, however, a very powerful compound magnetic battery is requisite.

Fig. 53.



Exp. 47. When a piece of copper plate was wrapped once round the iron cylinder *c d*, with interposed paper to prevent metallic communication, and the edges of the plate connected with two wires passing to the electro-magnetic multiplier G, fig. 53; then, on making contact with the

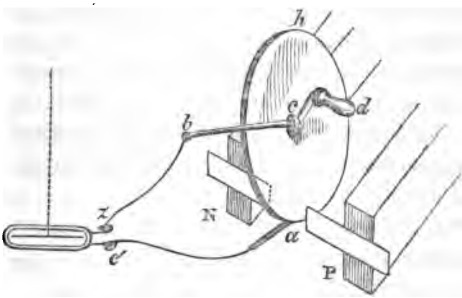
poles of the magnetic bars, the needle was deflected as before.

61. This effect has been termed magneto-electrical induction, and the current itself, magneto-electricity. The influence of the magnet in this case is considered as analogous in its mode of action to that of a wire carrying an electrical current on a similar secondary or passive wire placed very near it, and in which momentary electrical currents, sensible to the multiplier, are induced by the action of the primary wire, but in a reverse direction,—an effect which has been termed Volta-electric induction.

62. The inductive influence of the common magnetic poles, on an heliacal or convoluted wire, is also traceable in drawing a long slip or plate of metal through a small opening between them. Currents in this case also are induced in the metal, which flow at right angles to the direction of the motion of the plate, an effect which may be rendered extremely sensible in the following way.

Exp. 48. Mount a circular copper disc, *a b h d*, fig. 53, about a foot in diameter, and $\frac{1}{8}$th of an inch thick, on an axis *c*, in any convenient frame, and place two powerful magnetic poles P N on each side of its inferior edge *a*. Let a stout grooved wire *a*, bearing against the edge of the circumference of the disc, and immediately between the magnets, be connected with one of the cups of the coil of the multiplier *c*, and a similar wire *b c*, resting on the

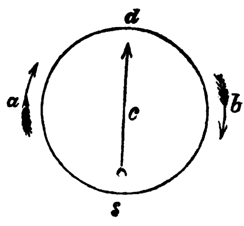
Fig. 54.



axis *c* of the plate, be made to communicate with the other cup of the multiplier; let the copper disc be now turned round between the poles of the magnets P N: immediately this is done, the needle of the multiplier is deflected, currents are induced in the disc, either flowing from the circumference at *a* to the centre *c*, or from the centre *c* to the circumference at *a* and its vicinity, according to the position of the magnetic poles, and the direction in which the plate is turned: these currents, returning between *c* and *a* through the coils of the multiplier, (which may be considered as a uniting wire) (40), deflect the needle from its position within the coil. If we suppose the disc to revolve directly in the line of the meridian, that is, towards the north, and the north pole P of the magnet to be on the right hand, then the current flows from the centre *c* to the circumference *a* and the neighbouring parts, and back again by the multiplier to the centre. If we reverse the motion, or change the poles of the magnets, then we reverse the direction of these currents.

63. It appears from these and many other similar experiments, that whenever any metallic substance is passed before a single pole, or between the opposite poles of a magnet, whether a metallic plate, slip, or even a long metallic wire, currents are induced transverse to the direction of the motion of the metal. Here then we have a fair explanation of this new species of force which Arago considered to exist in his experiments with a revolving disc and magnetic needle (58), and which it must be allowed differ materially from cases of ordinary magnetic action. If in the revolving disc, (58,) fig. 51, we take one of the radii in the direction of the magnetic meridian,—suppose the radius *c d* in the annexed fig. 55, *c* being the south, and *d* the north extremity,

Fig. 55.



and imagine that by the motion of the disc *a d b s*, in the direction of the arrows *a b*, a current of electricity sets from *c* to *d*, immediately under the magnetic needle *s d*,—then, by (*c*) Table I. (41), the north pole of the needle *d* moves to the right hand, and the south pole *s* to the left, that is to say, in the direction of the motion of the disc. Now we may consider the disc as made up of a succession of radii indefinitely near each other, and hence a continued current is produced immediately under the needle, which returns in remote portions of the disc, and by which the needle is first deflected and finally set into rapid motion; and thus we are enabled (41) to explain every circumstance connected with these interesting phenomena. Similar reasoning applies to the case of the rotation of a magnet under a moveable disc, it being evidently of no moment whether we suppose the disc in motion under the magnet, or the magnet in motion under the disc; in either case the force is reciprocal (44).

64. We may consider the tangential force in these cases to be resolved into two component forces, one parallel to the plane of rotation, and the other perpendicular to it: the first causes the circular motion, the last would be a repulsive force, as observed by Faraday, and is probably the particular force specified by M. Arago (59); and since without the motion of either the disc or the needle the electrical currents would not be induced, it further follows, that no attractive or other force is observable when the bodies are at rest.

If we suppose the copper disc, fig. 51, to be fixed, and the needle *m n* to be in oscillation over it, or that the needle be in oscillation within a ring of metal, fig. 50, there would necessarily arise a dragging or retarding force upon the needle, by which the extent of the vibration would be continually abridged, without the time of the vibration being affected; and hence the needle would be rapidly brought to rest; for since the disc cannot move and follow the oscillation, it must necessarily fetter the movement of the needle.

65. When a thick plate of iron is interposed between a

rotatory disc and a magnetic bar revolving over it, fig. 51, the motion is completely arrested; but mere plates of other substances were not observed to exert any influence in this way as a screen. By subsequent researches, however, it was found, that mass was requisite to this effect. Thus a mass of copper about 3 inches thick and a foot square, being interposed between a rotatory magnetic disc and a thin disc of tinned iron poised on a centre immediately over it, completely arrested the motion impressed on the iron. Silver, zinc, and other metals exert a similar influence, when employed in masses of sufficient magnitude to compensate for their respective magneto-electrical energies.* It is probable that this screening effect depends on similar principles to those already explained (38).

66. We may obtain a comparative numerical value of the magneto-electric energies of various substances by the following simple formula, $\left(\frac{a}{b} - 1\right) r$, in which a represents the number of vibrations of a magnetic needle in free space, taken between given arcs of amplitude, as, for example, between 45 degrees and 10 degrees; b, the number of vibrations within the same limits, under the influence of any particular substance, r being unity, as representing a constantly retarding force. Thus, if in free space (Exp. 43) a delicately suspended bar performs 420 oscillations before the arc of vibration is reduced from 45 degrees to 10 degrees, and that under the influence of two given and different metallic substances, the vibrations within the same limits are 30 and 20 respectively; then the energy of the one is represented by $\left(\frac{420}{30} - 1\right) r$, and the other by $\left(\frac{420}{20} - 1\right) r$, that is to say, they are to each other as 13 : 20.†

* Harris, 'Philosophical Transactions' for 1831, Part II. p. 497.

† A magnetic bar or needle vibrating under the influence of any given substance (Exp. 54) may be conceived to be reduced to rest by two

67. By a series of experiments which are detailed in the 'Philosophical Transactions' for 1831, Part I., it appears that the magneto-electric energy of bodies is directly as the mass of the substance within the limit of the magnetic influence, and inversely proportional to the square of the distance of any particle from the magnetic pole. As a consequence of this, it was found that the influence of the same substance on the magnetic needle is directly as its density. The following Table exhibits the relative energies of the metallic substances subjected to experiment, and calculated by the formula just given (66.)

TABLE III.—*Magneto-Electric Energy of Metals.*

Cast Bismuth	0·45
Fluid Mercury	1
Cast Antimony	1·3
Solid Mercury	2
Cast Lead	3·7
Cast Tin	6·9
Cast Zinc	10
Cast Gold	16
Cast Copper	20
Rolled Copper	29
Rolled Silver	39

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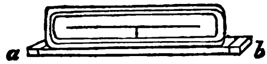
retarding forces, one which would reduce the bar to rest when vibrating alone, and the other emanating from the substance itself: call the first r, and the latter R, then we have for the combined or total force $r + R$. Let a be the number of oscillations in free space, and b the oscillations under the influence of any given substance; then since the number of oscillations may be taken as inversely proportional to the retarding forces, we have $a : b :: r + R : r$, or $a\,r = b\,(r + R)$. From whence we derive $R = \frac{a\,r - b\,r}{b} = \frac{a - b}{b} \times r = \left(\frac{a}{b} - 1\right) r$: but r being a constant force, may be taken as unity; hence the variable force of the different substances on the needle may be represented by $\frac{a}{b} - 1$; so that in dividing the number of oscillations in free space by the number under the influence of any given body, and subtracting unity from the quotient, we have a numerical value of the retarding force of the body.

68. A disturbance of the equilibrium of temperature is another source of electrical currents in metallic substances, and which flow between the heated and cooled parts, so as to deflect the magnetic needle, as in the previous experiment.

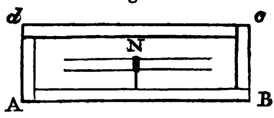
Exp. 49. Let the extremities of a rectangular coil of insulated wire, fig. 56, be attached to the opposite ends of a bar of bismuth *a b*, and a delicate needle suspended within the coil. Then, if heat be applied to one extremity *a* of the bar, the needle is immediately deflected; and this action is augmented if ice or other cooling substances be applied at the opposite extremity *b*.

Fig. 56.



When two different metals are united by soldering them together, then, by heating the metals at the point of junction, and cooling the more distant portions, this current action is very greatly increased. The most powerful combination appears to be that of antimony and bismuth.

Exp. 50. Solder together, at right angles to each other, four bars of antimony and bismuth, A *d d e*, and A B B *c*, fig. 57, so as to unite two combinations of such bars into a rectangular frame A *c*. Place an astatic needle N (29) within the rectangle, and apply heat to one of the junctions, A, by means of a spirit lamp, and keep the opposite angle *c* cool by means of ether dropped on a thin fold of muslin wrapped round the metallic joint. The needle N is immediately deflected from its position, and tends to stand at right angles to the rectangle, as in other cases of deflection (40.)

Fig. 57.

The intensity of these thermo-electrical currents increases with the temperature, up to a certain point, about 120° of Fahrenheit's scale; after this, that is, probably, when the

heat begins to pervade the metal more equably, the intensity of the current, in most instances, declines.

69. An opinion has been long entertained by philosophers, that, since iron loses its magnetic energy at a very high temperature, and regains it again as the temperature falls, there probably exists a low degree of heat at which all metallic substances would assume a magnetic condition, similar to that of iron. This view, however, has not been confirmed by experiment. Faraday, in 1839, reduced the temperature of antimony, bismuth, cobalt, copper, and various other metals, below $-110°$ of Fahrenheit's scale, but without developing in these bodies any kind of magnetic power. We have so far no evidence of what may be termed the direct magnetism of temperature.

70. Magnetic influence, as a universal agency, has been also extended to light, but with as little eventual confirmation by careful experiments. Dr. Morichini, an eminent physician at Rome, first called attention to an experiment in which a steel needle became magnetized by exposure to the violet ray of the sun. This experiment was repeated by several eminent persons, sometimes successfully, at others not. The talented and amiable Mrs. Somerville, amongst others, subjected a sewing needle to the influence of several rays of the spectrum, and found that the needle had become magnetic.

About the period of Mrs. Somerville's experiments, Mr. Christie, in a paper communicated to the Royal Society, in 1825, stated, that when a magnetic needle was caused to vibrate under the influence of the solar beam, the result was to augment the rate of the oscillation, and to bring the needle more rapidly to rest.

Notwithstanding all these results, it is still very doubtful whether the sun's rays have any direct magnetic properties. Faraday, who spent some time at Rome in 1814, failed, under Morichini's own direction, and working with Morichini's own apparatus, to magnetize a steel needle in the way described. The experiment, as admitted by Christie, further "failed in

the ablest hands." It is hence very probable that the magnetic condition occasionally found in steel needles on exposure to the rays of the sun, may have arisen from the heating and cooling of the steel, from position, or from some other of the many causes of magnetic change, of which steel is (especially in some specimens) so very sensible. There is also solid reason for supposing that the results arrived at by Mr. Christie, by the method of vibration, were dependent on the presence of the air, and other disturbing causes, which interfered with the accuracy of the experiment; since, on a repetition of the same course of inquiry, with the needles and other substances enclosed in an exhausted receiver, the supposed influence of the sun's rays altogether vanished. In this case, with a magnet oscillating in a void, the sun's ray had little or no influence on the arc of vibration, whilst the rate was rather retarded, probably by a slight expansion of the bar, or decrease of its magnetic tension by heat. Bars of copper and other non-magnetic metals, vibrating by the bifilar suspension, exhibited similar results, in air and in vacuo, as a magnetic bar, each being vibrated in the sun's rays, and in the shade. It is hence extremely doubtful whether magnetism, as a universal agency, extends to light, considered as a form of matter, more especially when we find that the most intense artificial light has no influence whatever on the vibrations of the horizontal needle.*

71. The progress of these very exciting inquiries into the operation of magnetism as a universal principle affecting every species of matter, has recently received fresh impulse from the genius of Faraday, who found that lines of magnetic force, in passing through certain transparent bodies, so affected their molecules as to impress on them a peculiar magnetic condition quite new to us, and by which a divided ray of light also passing through the body at the same time parallel to the magnetic lines, becomes bent, as it were, in its course, the

* Harris, Edin. Phil. Trans. vol. XIII. Part I.

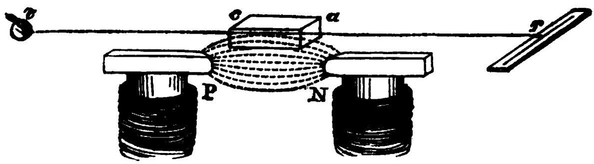
character of the force impressed on the ray being that of rotation.

72. By lines of magnetic force, we are to understand such forces as are exerted between two opposed magnetic poles (28), figs. 16, 17, 18: they may be either straight or curved.

Any substance through which such forces pass *without* rendering the substance magnetic, after the manner of iron, is termed a dia-magnetic substance, and the peculiar condition impressed upon its molecules by the transmission of the magnetic forces, dia-magnetism.

Exp. 51. If a divided and reflected ray of light, *r t*, fig. 58, be passed through a cube of heavy glass, *a c*, about

Fig. 58.



2 inches square and ½ an inch thick in the direction *t r* of its length, this cube being placed between the poles P N of a very powerful electro-magnet, and in such way that the ray *r t* and the lines of magnetic force between P N (28) may be nearly parallel to each other; and if previously to sending the current through the coils of the electro-magnet (53) we view the ray through an eye-piece, *t*, containing a crystalline substance, by means of which we can, in turning round the eye-piece on its axis, cause the image of the flame of the lamp from whence the light first proceeds to disappear; then, immediately we send the current through the coils of the electro-magnet, the image of the flame will again reappear, evidently showing that the ray had become bent or turned aside from its first course.*

* A ray of light, in passing through certain crystalline mineral substances, becomes split, as it were, into two portions, by some peculiar

When the image of the lamp flame has thus been rendered visible, the revolution of the eye-piece to the right or left, more or less, will cause its extinction. If the pole nearest the observer be a north pole, the ray rotates to the right hand; if the poles be changed by reversing the current, the ray rotates to the left hand; so that a magnetic line of force going from a north pole or coming from a south pole along the course of a polarized ray of light directed towards the observer, the dia-magnetic body through which the light passes will rotate the ray to the right hand: if, on the contrary, the lines of magnetic force come in the reverse directions, then the ray is rotated to the left hand.

By way of illustration, let a common watch be taken to represent a dia-magnetic substance, and suppose the north pole of a magnet applied to its face, and the south pole to its back, and a polarized ray of light to pass at the same time

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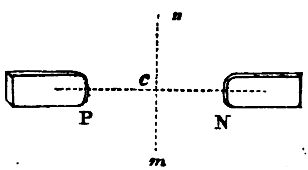
property of such bodies, thus giving origin to two distinct images. If these rays be now caused to pass through a second similar crystalline body, placed in a particular position, they are subjected to a still further division, and each ray undergoes a certain physical change: this physical change has been termed polarization. If we take then a fine plate of the tourmaline, for example, cut from the mineral in a plane parallel to the axis of the prism, we may perceive a candle through it as through a plate of coloured glass. If under these circumstances we interpose a second similar thin plate of tourmaline between the eye and the first plate, and turn this second plate slowly round upon a horizontal axis, the candle will disappear and reappear at every quarter of a revolution, according as the line of section of the two plates coincide or cross each other. If the original ray of light be reflected from a plane mirror at a given angle, and we examine this reflected ray by a single plate of tourmaline in a similar way to the preceding, the same thing occurs as with the two plates,—the image of the candle or lamp from which the rays proceed will appear and disappear at every quarter of a revolution. In the experiment above described, a prismatic eye-piece, termed a Nichols' prism, was employed, consisting of a crystalline substance capable of turning aside one of the rays and employing the other free from colour, and by turning round which, upon a horizontal axis, the image of the flame from the reflected ray could be made to disappear.

through the watch, from the back to the face, towards the observer; then the course of the hands of the watch is the direction, in this case, in which the ray is caused to rotate by the influence of the lines of magnetic force.* A great variety of other transparent bodies, such as flint glass, acids, alkalies, fixed oils, water, alcohol, ether, exhibit this curious phenomenon; but rock crystal, Iceland spar, and substances possessing the power of double refraction, have no such effect.

73. If the magnetic forces had magnetized the several transparent bodies employed in these experiments, then the molecular condition of a transparent magnet might probably have been examined by means of light; but since they did not, Faraday infers that their molecular condition is a new *magnetic condition*, and the force imparted to such bodies, a new *species of magnetic force*, or *mode of action* of common matter; and since the degree of transparency only makes a distinction between individuals of a class, it is to be inferred that similar forces arise in opaque dia-magnetic bodies whenever lines of magnetic force pass through them (72). We cannot, in fact, doubt that in the case of a transparent substance the lines of magnetic force act upon and affect the internal constitution of the body just as much in the dark as in the light, though it is solely by means of the ray of light that we are at present enabled to detect this particular condition of the molecules of matter.

74. When these substances which we have termed dia-magnetic (72), and which comprise a very extensive class of bodies, are delicately suspended between the poles of a powerful electro-magnet, they invariably stand transverse to the magnetic lines of force. Let, for example, P N, fig. 59, be the terminating poles of an extremely powerful electro-magnet, as in

Fig. 59.



* Faraday, 'Philosophical Transactions for 1846,' Part I.

fig. 58. We may term the intermediate space *c*, between these poles, the magnetic field,—the line of the poles P N, the axial line,—and the line *m n*, perpendicular to this and passing through the centre of the field, the equatorial line.*

Exp. 52. Let a bar of heavy glass or any of the substances not magnetic, after the manner of iron, be suspended by a silk fibre, so as to hang in the centre *c* of the magnetic field or space between the poles P N, fig. 59; pass a strong current through the coil; the bar, if previously settled axially in the line P N, will now vary from this position and settle in the equatorial line, *n c m*.

If the substance be near one of the poles, that is, out of the centre *c*, then on pointing equatorially it is apparently repelled, and this repulsive effect is common to both poles, so that we have in this case magnetic repulsion without polarity (7).

75. A large number of bodies have been thus subjected to experiment and found productive of similar results: amongst these we find wood, animal fibre, and common vegetable matter; so that if a man could be suspended with sufficient delicacy in the magnetic field between the poles of a powerful magnet, he would point equatorially, and be repelled by both poles; for all the substances constituting the human frame have this property.

76. Metallic bodies, as a class, are found to exhibit highly interesting and distinctive characteristics in regard to this new species of force; and the powerful operation of the electro-magnet determines at once whether they are to be considered as magnetic substances or not. If magnetic, they would point axially; if dia-magnetic, equatorially (74); if near one of the poles, they would as magnetic bodies be attracted; if dia-magnetic, they would be repelled. On submitting metallic substances to this test, iron, nickel, cobalt were at once found to be magnetic bodies,—they all pointed axially: to these

* Faraday, 'Experimental Researches,' nineteenth series.

may be perhaps added, platinum, palladium, and titanium: all the other metals, antimony, bismuth, copper, gold, &c., were found to stand transverse to the lines of magnetic force and to be repelled by both poles.

77. The dia-magnetic force manifested by different metals varies considerably in degree. Bismuth, which has the least magneto-electric energy of all the metals (67), Table III., has the greatest dia-magnetic power. Antimony, another metal low in the scale of magneto-electric energy, also exhibits considerable dia-magnetic force. It is further remarkable that copper and silver, the highest in the scale of magneto-electric energy (67), have the lowest dia-magnetic force.

The repulsion of bismuth and antimony by the poles of the magnet appears to have been noticed twenty years since by Baillif, of Paris, although under circumstances widely different from those of Faraday.

78. On submitting magnetic and dia-magnetic metals to the influence of heat, a decisive difference is still manifest between them. The decidedly magnetic metals, iron and nickel, still point axially and are attracted by the magnet, even when they are heated to such an extent as to annihilate their influence on common artificial magnets: hence these metals are not thus far reducible to a pure dia-magnetic condition. Such facts therefore are subversive of the opinion (69) that every metallic substance would probably assume a magnetic condition similar to iron if subjected to very low temperatures.

79. These very important inquiries being perfectly original and new, are clearly separable from the early experiments of Coulombe (56), and the subsequent investigations of M. Becquerel (57). The discrepancy which appears to have arisen in the case of Coulombe's experiments, in which needles of various substances were found to settle in the line of magnetic force and point axially, is by no means inexplicable. First, the very great power of the electro-magnet employed by Faraday, at once places the experiment in a condition more favourable to a correct result. This magnet could sustain a hundred

weight at each pole. The form and size of the magnetic poles in Coulombe's experiments, as compared with the size of the needles,—the possibility that the substances tried contained very small portions of iron, and the interference of many circumstances, of which Coulombe was not aware, but which have since led to singular precautions in this kind of research,—all tend to show not only the possible but probable cause of the difference which appears to have arisen in the two experimental investigations. Even with the intense magnet used by Faraday, very great caution was found requisite in the manipulation, in order to arrive at an unmixed result. The repulsion of both bismuth and antimony by the magnetic poles has been observed and recorded by Brugmans in 1778, by M. Baillif in 1827, and by other philosophers; yet we may infer from Coulombe's results that needles of these substances, in common with all other matter, pointed axially. It was not, however, always that substances took an axial direction in these experiments, as admitted by M. Becquerel; in several instances they stood transverse to the lines of magnetic force. In M. Becquerel's subsequent inquiries this was especially observable with certain oxides of iron, and also with needles of wood and gum lac, when placed in a certain relative position to the magnetic pole (57). M. Becquerel hence concludes, that the only difference in the magnetic condition of bodies when pointing equatorially, is that they become magnetized transversely or across their length. Faraday's researches, however, very completely set this question at rest. The position of the bodies in M. Becquerel's experiments with the oxides of iron, is an unstable, and in many cases an uncertain position, whilst the centre of gravity of the suspended system is always attracted by the magnetic poles; whereas in the case of pure dia-magnetic action, the equatorial position assumed by these substances is a position of stable equilibrium, and from which, if the bodies be deflected or turned aside, they will invariably return to again, and with a sensible degree of force: instead of being

attracted by the magnetic poles, they are always repelled. These beautiful and most important researches must therefore be considered as entirely distinct and independent of all former experiments, and as very clearly establishing the existence of a new magnetic condition of matter hitherto unknown to us.

80. Upon a review of the whole course of inquiry from the time of Coulombe's experiments in 1800 to the present day, we are driven to the conclusion, that all matter is not susceptible of ordinary magnetism after the manner of iron; that the class of what may be termed magnetic bodies is in this sense very limited, being confined principally to iron, nickel, and cobalt, to which we may add perhaps, although with a less degree of certainty, palladium, platinum, and titanium. On the other hand, by the discovery of dia-magnetic action, the question of universal magnetism becomes placed in a new and very different light. In this case we arrive at the existence of magnetic forces the very opposite of those existing in common magnetic bodies; the first lead to attraction, the latter to repulsion, yet we may fairly conclude that all matter is susceptible of magnetic influence under one or the other of these forms, that is, either magnetically after the manner of iron, or dia-magnetically after the manner of bismuth. In this sense magnetism may be considered as a universal agency. Instead, therefore, of associating bodies under the two classes of magnetic and non-magnetic bodies (54), we should distinguish them as magnetic or dia-magnetic bodies, and between which there is evidently a definite and striking contrast.

The following order of metallic substances in the scale of universal magnetic force has been derived from Faraday's papers; and although open to future correction, it is still extremely useful in the way of reference:

Magnetic.	*Dia-magnetic.*
Iron.	Bismuth.
Nickel.	Antimony.
Cobalt.	Zinc.
Manganese.	Tin.
Chromium.	Cadmium.
Cerium.	Sodium.
Titanium.	Mercury.
Palladium.	Lead.
Platinum.	Silver.
Osmium.	Copper.
	Gold.
	Arsenic.
	Uranium.
	Rhodium.
	Iridium.
	Tungsten.

0

The scale here, as in the classification of electrics and conductors,* runs through neutrality from two extremes: the zero point is to be taken as the condition of indifference to either magnetic force, viz. attraction or repulsion;—the further any metal stands from this point, the more perfect it is of its class.

* 'Rudimentary Electricity,' p. 8.

V.

MAGNETIC INSTRUMENTS, THEIR CONSTRUCTION AND USE.

Artificial Magnets — Conversion of Iron into Steel — Temperament — Various Processes of Magnetizing—Compound Magnets—Magnetic Machines — Magnetoscopes and Magnetometers — The Compass — Various Instruments for Determining and Measuring the Hourly Changes and Declination of the Vertical and Horizontal Needles.

81. The extensive application and importance of magnetism to practical purposes has necessarily led to the construction of a great variety of magnetical instruments. These may be separated into the following classes:

1. Instruments for the accumulation and development of magnetic power.

2. Instruments for detecting the presence, indicating the polarity, and measuring the amount of magnetic force.

3. Instruments for determining the direction and measuring the declination of the horizontal and vertical needles (24), under a variety of circumstances and conditions, and at any instant.

82. Instruments for the accumulation and development of magnetic power consist principally of artificial magnets (19), simple and compound; combinations of compound magnets, termed magnetic machines; and the electro-magnetic spiral (53).

We have seen (Experiment 17,) (32), that when a mass of iron is applied to the pole of a magnet, it becomes powerfully magnetic; the susceptibility, however, of this excitation is less in hard and brittle pieces of iron or steel than in pieces which have been softened by heat. Hard steel, however, possesses, on the contrary, as before observed (16), a greater

retentive power. The magnetism developed in a piece of soft iron T, fig. 24, vanishes, or nearly so, directly we remove the iron from contact with the magnet; whereas in substituting a piece of very hard steel, although requiring a higher degrée of power for the development of its magnetic energy, we find the magnetism induced in the steel permanent. The magnetic susceptibility and the retentive power are consequently in some inverse proportion to each other. As a first or leading principle, therefore, in the production of magnetic machines, we must seek to obtain the greatest amount of susceptibility consistent with a high retentive power in the steel.

83. We have already described (19) the principal kinds and forms of artificial magnets. These we have found to consist of straight or curved bars of hard steel in which magnetism has been excited by the aid of the natural or other magnets. Now, the degree of force which can be thus produced in bars of steel will be further dependent on the proportion of the surface of the bar as compared with its bulk, all other things being equal. A thin steel plate, for example, may have a much higher degree of *proportionate* magnetic power excited in it than the same quantity of the like steel disposed under a more concentrated form, a result probably dependent on the fact that the magnetic excitation does not reach far beneath the surface (27). Dr. Ingenhous (Phil. Trans. 1779) constructed a small magnet of several laminæ of magnetized steel firmly pressed together, which he found would sustain 150 times its own weight,—a force quite unknown in a single bar of the same dimensions.

84. The best relative dimensions, however, for magnetic bars for general purposes will in some degree vary with the length of the bar, and the particular experimental object in view. Cavello recommends for bars of about 5 inches in length, that the breadth be one-tenth part of the length, and the thickness one-half the breadth. Canton gave to such bars a breadth of about the one-eleventh part of the length, and a thickness rather less than one-third the breadth.

Coulombe, in his compound magnets constructed of bars 21 inches long, made their breadth about the one-thirty-fifth part of their length, and the thickness one-third the breadth. In the more early experiments by Dr. Gowan Knight, the breadth of his magnetic bars was from one-twelfth to one-fifteenth their length, and the thickness one-half the width. For bars of about 2 feet to 30 inches long, the breadth may be about the one-twentieth of the length, and the thickness something more than one-third the breadth. Bars intended for magnets of the horse-shoe form (19), fig. 8, may have a greater length in proportion to their width than ordinary straight bars.

85. Another great point which we have to consider in the construction of artificial magnets and magnetic machines, is the kind and quality of the steel, together with the degree of hardness or temperament to which it has been subjected.

When pure malleable bar iron has been slowly and for a long time heated in a closed furnace, in contact with pulverized charcoal, and subsequently allowed to cool gradually for a space of several days, the texture of the metal becomes changed; it loses much of its ductility and malleability, but gains in hardness and elasticity; it has united with a certain portion of carbon, and has been converted into what we call steel.

86. Steel, when suddenly cooled from a high point of temperature, becomes extremely hard and brittle: hammering will also harden steel very considerably; but the most effective method of hardening steel bars intended for artificial magnets, is to raise the temperature of the bar to a bright red or even white heat, and then plunge it into cold-water brine, or some other cold liquid, such as oil. Steel thus treated resists the action of a file, and may be made to scratch glass like the diamond.

87. After being thus hardened, steel may be again softened to any required degree by the process called tempering, which consists in again exposing it to heat on a plate of red hot iron,

As the heat begins to permeate the metal, the surface will be observed to pass through successive changes of colour. First, it will appear to assume a red or purple tint; then a yellow or straw colour; this gradually deepens and changes to a light blue; we have then a deep blue; finally, the steel becomes red-hot.

We are enabled by these various tints to estimate the degree of hardness retained by the steel at any moment, and may hence, by its removal from the iron at that moment, obtain the precise degree of hardness we require. When we perceive the straw colour, the steel will have become a little softened; it is then in a fit state for certain tools, such as drills; this point has been termed 'drill temper.' When the colour has changed to a blue, it is then in a fit state for springs of various kinds; this point has been termed 'spring temper:' we may therefore, by a little practice, temper steel to any required point.

88. The process of converting iron into steel, and its subsequent treatment, has given origin to several different qualities and kinds of steel, all of which have received some distinguishing term.

During the first process of cementation with charcoal (85), the surface of the iron frequently becomes blistered by the heat. Bars in this state constitute what is called 'blistered steel:' these bars of blistered steel, when exposed again to heat, doubled, welded together, and again drawn out, produce what is termed 'shear steel,' of which kind we have the single and double shear steel, according to the extent of the process of conversion.

When blistered or unrefined steel is fused in a crucible with a little charcoal or black oxide of manganese, in a wind furnace, it may readily be cast into ingots or bars; this is denominated 'cast steel.' Thus treated, the steel acquires a more uniform texture and a closer grain, and is harder or softer according to the quantity of the flux employed: when subjected to the action of the hammer, the texture becomes

still more compact, constituting hammered cast steel, one of the most valuable forms of steel as yet obtained.

89. Of these different kinds of steel, the hammered ingot steel, made from very good Swedish iron, smelted with wood charcoal of the first quality, may be considered as being well adapted to the purposes of artificial magnets. We are still, however, open to accidental varieties of quality almost impossible to avoid. If the steel, when fractured, exhibits a uniform and small silvery granulated appearance, it will be found, on being properly tempered, susceptible of a high degree of magnetic development. It is always, however, difficult to furnish a universal reply to the question—what is the best kind of steel for magnets, and what degree of temper or hardness should be given to it? The Rev. Dr. Scoresby, to whose unwearied labours in this department of science we are indebted for a most complete and extensive series of experiments and investigations relative to this question, gives the following general deductions.*

For straight bar magnets of a massive kind (84), the best cast steel, made quite hard, should be employed.

For compound magnets, constructed of thin plates of what is called 'steel busk,' the best cast steel hardened to the greatest possible degree by means of oil.

For single horse-shoe magnets, also the best cast steel, tempered from file hardness at about 550°, or shear steel a little reduced.

For compound horse-shoe magnets, cast steel tempered at from 480° to 500° Fah., or shear steel rendered perfectly hard.

The limits of the degree of hardness the most effective for all practical purposes are comprised between the brittle hardness of files and that of elastic spring temper.

90. Coulombe employed a kind of steel termed '*d'acier timbré à sept étoiles*,' the bars being tempered at a cherry-red heat. M. Biot, as just remarked, recommends the bars to be

* 'Magnetical Investigations,' Part II. p. 282.

first made as hard and brittle as possible, in which case they will be frequently warped and distorted; then to let them down to a temper indicated by the first shade of yellow (87), at which point they may be set straight with a hammer.*

METHODS OF COMMUNICATING MAGNETISM TO STEEL BARS.

91. The first means of imparting magnetism to steel, was, as we have already described (16), by contact with the armed lodestone or other magnet. A more efficacious method, however, of magnetizing small needles or bars by simple contact, consists in placing the bar or needle between the opposite poles of powerful magnets, as for example in the magnetic field S N, fig. 17, page 24, immediately between the poles S N.

92. We are indebted to Dr. Gowan Knight, F.R.S., a London physician, for the first important step in the communication of magnetism to bars of steel. His method, as given in the Philosophical Transactions for the years 1746 and 1747, vol. XLIV., is as follows: two powerful magnetic bars M M′, fig. 60, are placed in the same straight line, with their opposite poles N S

Fig. 60.

very near each other; the needle or bar, *n s*, to be magnetized is laid flat on the surface of the bars immediately over the opening N S, between them. If the bar *n s* be a magnetic needle having a cap for suspension, then the cap is allowed to rest between the bars: if the surface be unimpeded by this, the

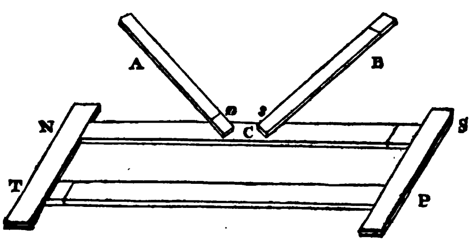
* In giving steel bars the precise degree of hardness required, it is desirable to let them down from extreme hardness, as recommended by Biot: great uncertainty often arises in the tempering of bars, in the common method of plunging them into cold water at low degrees of heat; thin plates may be rendered quite brittle, whilst thick bars are often but slightly acted on.

bars M M′ may be brought very near each other. Things being thus disposed, the bars M M′ are gradually withdrawn in opposite directions, and immediately under the bar *s n*; the result of which operation is, on the principles already explained (17), that each half of the bar *s n* being acted on by opposite polarities, the two magnetic forces resident in it become separated; the pole N of the bar M attracts all the south polarity and repels the north, whilst the pole S of the bar M′ attracts all the north polarity and repels the south: hence a final and permanent magnetic state is imparted to the bar *s n*, the position of the poles *s n* being the reverse of the poles N S of the bars (17).

Small needles will become magnetized to saturation by one operation of this kind performed on each of its surfaces; for larger bars, two or three or more repetitions are desirable. This method is very effectual, especially for single bars, and there is not, perhaps, any better for certain purposes, even at the present day.

93. After this method of Dr. Knight's had become known and practised, M. Du Hamel, member of the Royal Academy of Sciences at Paris, was led, about the year 1749, to a further and still more extensive application of it. Two bars, N S, and T P, fig. 61, required to be magnetized, are laid on a table

Fig. 61.



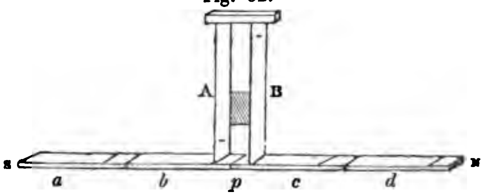
parallel to each other, and their intended opposite poles united by pieces of soft iron N T, S P, so as to form a closed rectangular parallelogram, as seen in the figure.

The opposite poles *n s*, of two powerful magnets A B, either simple or compound, are then applied to the centre, C, of one of the bars N S, and drawn away from each other in opposite directions, C N, C S, being held all the while at an inclination of about 40°: this operation is repeated several times; the magnets A B are now either reversed, or their relative positions changed, by turning them round; they are then applied in a similar way to the other bar, P T, so as to bring the poles *s n* opposite to their former position: the same operation is now repeated on the bar T P, and this process is to be further repeated on each surface of the bars T P, N S. M. Du Hamel's method is effective and expeditious; the elementary forces resident in the bars being by the joint operation of the magnets easily separated (14), whilst the union of the opposite poles N T and S P, by soft iron, further tends to increase the effect, by holding together, as it were, the two separated magnetic elements, and thus allowing the exciting magnets A B to operate with more considerable effect.

Bars of the horse-shoe form may be rendered magnetic in a similar way, by uniting their near extremities or intended poles with soft iron, and then drawing the magnets away from each other, commencing at the centre of the curve, and terminating at each extremity.

94. Mr. Michell of Cambridge, and Mr. Canton, in 1750 or 1751, still further advanced this department of practical magnetism. Michell employed a method which he designated as 'the double touch.' Several bars *a b c d*, fig. 62, to be magnetized, are placed in one straight line, the intended opposite polar extremities being in contact: thus the north pole of the bar *a* is placed in contact with the intended south pole of the bar *b*, and so on: the bars

Fig. 62.



being thus disposed, the opposite poles of two powerful magnets, A B, either single or compound, are placed about the centre of the series, the opposite poles beneath resting one on each side the centre *p*, whilst the distant opposite poles are joined by a piece of soft iron: the system thus formed is now moved backwards and forwards over the line of bars from one end to the other, taking care (17) that the south pole of the system A B applies to the intended opposite pole N of the series of bars S N, and reciprocally, the north pole to the intended opposite pole S: the operation is to be repeated several times on each surface of the bars, and the system finally removed at the centre *p* of the chain. By this operation, the centre bars *b c* will be found to have acquired a high magnetic development, the extreme bars *a b*, not so high; these are to be now shifted from the extremities to the centre, and to be replaced by the centre bars *b c*, when the same process is to be repeated. In this experiment, the extreme bars *a d* may be conceived to act as the connecting pieces of soft iron N T, S P, fig. 61, employed by Du Hamel, and the magnetic elements become separated in precisely the same manner; each polarity *s n* of the system A B repels one of the magnetic elements (14), and attracts the other, so that by the reciprocating rectilinear motion, one polarity is determined in one direction, and the converse polarity in an opposite direction. On dislocating the chains of bars, we find each bar a complete magnet.

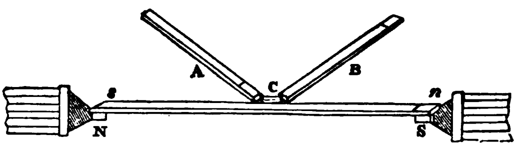
95. Soon after Michell published this method in 1750, Canton gave a process in which the methods of Michell and Du Hamel were combined. The bars to be magnetized were placed in series, as recommended by Michell, but arranged in two parallel lengths, with connecting pieces of soft iron, as in the rectangle of Du Hamel, fig. 61; they were then rendered magnetic by the double touch (94).

96. Æpinus adopted Du Hamel's rectangle of single bars, but closed the rectangle, fig. 61, with magnetized steel instead of soft iron, taking care to place the marked and unmarked poles next each other; the bars were then rubbed by the method of the

double touch prescribed by Michell: instead, however, of resting the magnetizing system A B, fig. 62, upright on the bars, the magnets were inclined to each other at an angle of about 25°, after the manner of Du Hamel, as represented in fig. 61, the bars being drawn backwards and forwards together in the same direction.

97. Coulombe was in the habit of magnetizing straight bars by resting the bar *n s*, fig. 63, on the polar projections S N of two powerful compound magnets (19): in this position

Fig. 63.



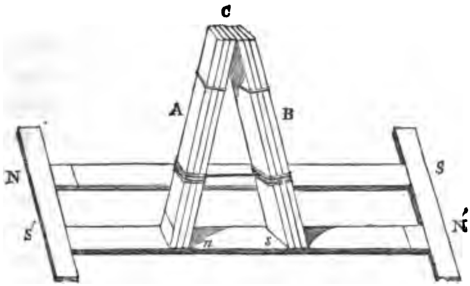
it was touched by two inclined systems or bundles of bars, A B, as in the last method; a small block of wood or metal, C, being placed between the opposed poles, and the operation always concluding at the centre C of the bar, care being taken to oppose the reverse polarities to each other (17). When the magnets or bundles of bars move together and in the same direction, we may with advantage substitute for the system A B, fig. 61, a powerful compound magnet of the horse-shoe form, as before explained (20).

98. A high magnetic development may be obtained in a series of straight bars, without the aid of powerful magnets, by a successive touching in combination one with the other. We are indebted to Mr. Canton for this process, which is as follows:

Having a set of 12 bars, however slightly magnetic, two of the series S′ N′, N S, fig. 64, are laid with reverse poles parallel to each other, and the rectangle closed by pieces of soft iron S N′, N S′, about one-half the length of the bars, and of the same breadth, as in the method of Du Hamel (93); the remaining 10 bars are separated into two com-

bined systems A B, of 5 bars each, placed on one of the bars, N′ S′, with their remote and opposite poles C in

Fig. 64.



contact, and their lower poles *n s* somewhat open. This arrangement being made, the bars S′ N′ and N S are rubbed with these systems in the way already described (94), and being thus strengthened by the united powers of all the rest, are now removed, and placed at the back of the others, as at A B, whilst the two interior bars of each system, C *s*, C *n*, are withdrawn, and subjected to the same operation as the preceding: in this way we continue to strengthen each pair of bars by the acquired power of those last touched, until the whole become magnetized to saturation. This process is very useful when powerful magnets are not at hand; for however weak may be the magnetic state of the bars, even although two of them only be slightly magnetic, we may from these render the whole series very powerful.

The combined systems A B may be temporarily bound together by a little common tape, and a small block of wood placed between them, so as to support the whole in position during the process of magnetizing.

99. All these various methods of magnetizing steel bars by the influence of already existing magnets may be advantageously resolved into two simple processes, viz. the original process of the single touch by Dr. Gowan Knight, fig. 60, and

the method of the double touch by Michell, fig. 62, but somewhat differently applied.

Scoresby, in his 'Magnetical Investigations,' especially recommends Dr. Knight's method (92) for magnetizing thin plates and bars up to the measure in length and breadth of the magnets employed, and carries it out in the way first practised, that is, by placing the magnets under the bar to be magnetized as in fig. 60, and not over it as in fig. 61, which is usually done. The following is Dr. Knight's process, as practised by Scoresby:

Two powerful bar magnets, tempered and magnetic throughout, are placed in a straight line with their opposite poles near each other, as already shown, fig. 60: the plate or bar to be magnetized is laid flat on the bars, extending equally over the surface of both. The magnets are then drawn asunder in opposite directions under the plate, until the plate rests with its extremities in contact with the extreme poles of the two bars; it is then slid off sideways, removed to some distance, but still kept parallel to the bars, which are to be restored to their former position, and the plate replaced for a new operation. This process is repeated on each surface of the plate, after which it will be found magnetized to saturation. A dozen plates or bars may be magnetized in this way in a few minutes, and plates or bars, of 16 inches to 2 feet in length up to a quarter of an inch thick, may be magnetized within a minute.*

With a view to facilitate the manipulation, the magnetic bars are placed on a flat board between two guides of wood, by which the line of direction is in the course of separation effectually preserved. A small pin is fixed in the middle of the groove formed by the guides, by which the poles of the opposed magnets are prevented from actually closing upon each other; there are also two other pins at the extremity of the distance required to withdraw the magnets, adjusted to

* 'Magnetical Investigations,' Part I. Chap. II.

the length of the bar to be rendered magnetic, by which the further separation of the magnets is checked at the instant required.

100. To magnetize large bars in pairs, the process already described (20), fig. 11, will be found the most ready and efficient, the bars being arranged as in the process of Du Hamel and Æpinus. This is unquestionably the best method of applying Michell's double touch, care being taken to place the opposite poles next each other (17).

Curved bars of the horse-shoe form are best treated also in pairs, as in the annexed figure 65, placing the opposite or

Fig. 65.

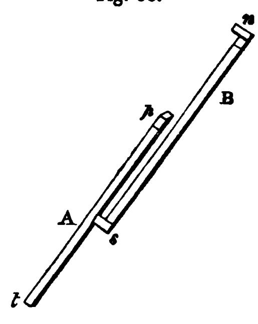
marked and unmarked ends against each other: thus placed, a powerful compound magnet is then applied on the centre *c* of one of the curves, as in fig. 12, page 17, and glided quite round the whole circle until we arrive at the centre *c* again: this must be repeated several times, when the magnet is to be removed; the curved bars are then to be turned over, and the process repeated on the opposite surfaces: to facilitate the manipulation, the bars may be confined to a flat board by small pins at *c c'*. This method is only an extension of that already given, page 17. Barlow adopts Canton's arrangement already described (95), viz. the placing two lines of bars in series (94), and completing the rectangle with magnets or soft iron. A powerful compound magnet is then glided round the whole series of bars after the manner just described. From 12 to 36 bars may be rendered magnetic in this way in about half an hour.

101. Beside these direct methods, we have other processes for obtaining a magnetic development in steel and iron, of much practical importance. Marcel, so long since as the year

1722, observed that a bar of iron acquired a temporary magnetic state by position alone (12); and he succeeded in imparting magnetism to a piece of hard steel placed on an anvil, merely by rubbing it with the lower end of a bar of iron about 33 inches long, set upright upon the steel. The temporary magnetic state thus induced by position in the iron bar is such that the lower extremity, in these latitudes, becomes a south pole, and the upper extremity a north pole; and the forces are much increased by placing the bar in the direction of the inclined needle (21): in southern latitudes the reverse of this occurs,—the lower extremity is then a north pole and the upper end a south pole. Mr. Canton, by an ingenious manipulation of this kind, succeeded in communicating a weak degree of magnetism to steel by means of a common poker and a pair of tongs, and from this magnetized his series of bars to saturation by the process we have described (98): the bar to be rendered weakly magnetic was attached to the upper end of the poker by means of thread, and the whole placed in the direction of the dipping needle (21); whilst in this position the bar was repeatedly touched with the closed extremities of the tongs, carried from one end of the bar to the other, from below upward, the marked end of the bar being below.

102. Savery, in 1730, succeeded in magnetizing bars of hard steel $\frac{3}{4}$ths of an inch square and 16 inches long, by fitting an armature at each end of one of the bars, and touching the other bars with it whilst held in an inclined position, as represented in the annexed figure 66. Savery's process was very ingenious, and is worthy of notice. Having fitted two small armatures of iron, *s n*, to one of the bars B, he held it in the magnetic meridian in the line of the inclined needle (21); then bringing a second bar A into a similar position with

Fig. 66.



its marked end *p* uppermost, he brought the small armature *s* near its lower end *t*, and then proceeded to touch the bar throughout its length by gliding the armature *s* nearly to the end *p*. This process being repeated several times, he proceeded to apply the opposite armature *n* in a similar way to the extremity *p*, and then to touch the bar A in the reverse direction. Having in this way developed a small degree of magnetism in the bar A, he removed the armatures from B, and applied them to the weak magnetic bar A; he then proceeded to touch B in a similar way, taking care to place the marked end of the bars uppermost. By an extension of this process in changing the armatures from bar to bar and touching the weakest, he obtained a sufficient degree of power to lift a key weighing more than an ounce. From these bars he was enabled to magnetize several others by fixing them in series on a board with reciprocal poles one over the other (94), inclining the board in the direction of the dipping needle. In this position he touched the whole series as before with each of the armatures alternately applied, first in one direction, then in the other; and so by changing the touching bar from time to time, as the series increased in strength, and allowing each bar to take up a new place, he at length obtained sufficient power to lift one bar with another at their opposite poles. The bars employed in this experiment were of hard steel, 16 inches long and $\frac{3}{4}$ths of an inch square, and weighed about 3 lbs. each. Michell, who adopted Savery's process, placed the steel bar A, fig. 66, between two large bars of soft iron: by this the effect appears to have been considerably increased.

103. Another method of developing magnetism in steel bars, without the aid of common magnets, consists in subjecting the bar to sharp concussion. This principle was well known to Gilbert so long since as the year 1570, who in his celebrated work 'de Magnete' represents a blacksmith hammering a steel bar in the position of the inclined needle. Smiths' tools, such as drills, broaches, &c., which have undergone pressure and motion, are generally magnetic. When a

steel punch is driven hard into iron, the punch is not unfrequently rendered magnetic by a single blow.

In the Philosophical Transactions for 1738 we find an account, by Desaguliers, of iron bars rendered magnetic by striking them sharply against the ground whilst in a vertical position, or otherwise striking them with a hammer when placed in a horizontal position at right angles to the magnetic meridian. Such bars attract and repulse the poles of the needle. According to Du Faye, whose experiments are quoted, it is no consequence how the bar is struck: all that is required is to impart to the bar a vibratory state whilst in a vertical position.

104. Availing himself of these facts, Scoresby, after a further and critical examination of the subject, succeeded in obtaining magnetic bars of extraordinary power by percussion. In the course of these inquiries, a considerable advantage was found to arise by striking the bar whilst resting in a vertical position upon a rod of iron. A cylindrical bar of soft steel $6\frac{1}{2}$ inches long and $\frac{1}{4}$ of an inch diameter, resting on stone and struck with a hammer weighing 12 ounces, could only be made to lift about $6\frac{1}{2}$ grains; whereas when resting on a bar of iron, and struck in a similar way, it lifted 88 grains. Scoresby, in developing magnetism in this way by percussion, first struck a large iron bar in a vertical position, and then laid it on the ground with its acquired south pole towards the north; he then proceeded to strike sharply with a hammer a soft steel bar 30 inches long and an inch square, resting vertically on the south pole of the iron bar. A second similar bar was treated in the same way; then, placing one of these steel bars vertically, he proceeded to strike upon them, as supports, a series of flat bars of soft steel 8 inches long and $\frac{1}{2}$ an inch broad, and in a few minutes they had acquired a considerable lifting power. The series of bars being now touched one with the other after the manner of Canton (98), became very soon magnetized to saturation: each pair readily lifted 8 ounces.*

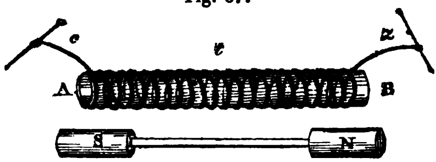
* Philosophical Transactions for 1822.

Dr. Scoresby observes that large iron and steel bars are not absolutely requisite to the success of this process, common pokers answering the purpose very well.

105. The most powerful method of developing magnetism in iron and steel, without the aid of ordinary magnets, is certainly by means of the electro-magnetic spiral (52), or by the transmission of electrical currents about the steel, in the way and on the principles before described (53).

The kind of apparatus employed for this purpose consists of a stiff paste-board tube, A *t* B, fig. 67, about 20 inches long and 2 inches in diameter: a stout copper wire, *c t z*, about ¼ of an inch diameter, covered with silk thread, is coiled closely

Fig. 67.



round this cylinder, terminating in two moveable jointed wires *z c*. The bar, N S, to be rendered magnetic is placed between two cores of soft iron N S; each about 8 inches in length, and turned to fit the case A B, and the whole is placed within the spiral coil *c t z*. This being arranged, contact is made between the terminating wires *c z* and the plates of four cells of Grove's powerful battery (47). Supposing the spiral coil to be direct (51), and the current to flow from *c* to *z*, so as to descend the coils *t* next the observer, then the right-hand extremity N of the bar S N will become a north pole (52).

By employing spiral coils of this kind, of sufficient magnitude, any steel bar may be at once magnetized to saturation: small bars and needles will at once receive a maximum degree of power. Bars of the horse-shoe form may be rendered magnetic in a similar way, by winding a coil of covered copper wire round them, from end to end, and then subjecting the coil to contact with the zinc and copper plates of a Voltaic circle (40).

106. A temporary electro-magnet of soft iron rod (53) may be advantageously employed as a means of touching steel bars.

In fact, when the arrangement is of some considerable extent, nothing can resist it: small needles and bars will become magnetized to saturation by mere contact with its poles. If the system be fixed and unwieldy, with the poles uppermost (fig. 58), means must be devised to move the bars upon or very near the poles, according to any of the processes before given, which may be done without any great mechanical difficulty by securing the bars to a flat board, of sufficient extent to fix them in position; for example, according to the methods of Du Hamel, Michell, Æpinus, and Coulombe, (93 to 97.)

In smaller electro-magnets (53), we may, by mounting the system on a light wheel-carriage, together with the Voltaic circle (47), proceed to employ the poles of the magnet through the platform beneath, in the same way as those of the common horse-shoe magnet (20), the whole being made moveable over the bars. It will be convenient, in this case, to support the electro-magnet on a central standard, with a screw for elevating or depressing it by a small quantity, and so adjusting the poles to the surface of the bars beneath.

107. *Compound Artificial Magnets.*—These, as we have seen (19), consist of many single magnetic bars, either straight or curved, united together in series or bundles, the similar poles being all laid together, so as to obtain as far as possible the accumulated force of the whole. There are several methods of associating and arranging magnetic bars in fasciculi or other forms of union.

The first of these claiming especial notice are the methods of Coulombe and Biot. The compound magnets of Coulombe consisted of moveable and fixed bundles of straight bars, such as are represented in the annexed figures, in which fig. 68 represents a small moveable combination, and fig. 69 a massive or stationary combination.

Fig. 68.

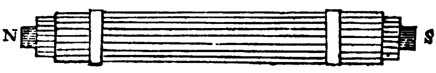


Fig. 69.

The small or moveable bundle, fig. 68, consists of four magnetic bars, from 15 to 16 inches in length, ·6 of an inch wide, and ·2 thick: these having been tempered at a cherry-red heat (86), were united at each extremity, N S, fig. 69, upon a small rectangular parallelopiped of very soft iron, *a b*, and in pairs of two bars each, superposed one upon the other, and placed side by side, so that the resulting bundle was 16 inches long, about $1\frac{1}{4}$ inch wide, and something less than half an inch thick, allowing for the intervening iron armature. The whole bundle is held together by bands of brass or copper, as at *n c s*, fig. 68.

The stationary or fixed bundles, fig. 69, consisted of ten magnetic bars, about 21 inches in length, and of the same breadth and thickness as the former: these ten bars were disposed in two layers, or beds, of five bars each, placed side by side, and superposed upon an intermediate armature of rectangular parallelopipeds of soft iron, which, projecting from between the layers of bars, as represented at N S, fig. 69, concentrate the attractive force, and form the armature and poles. The whole is held together by metallic bands, as in the former case.

Coulombe employed these fixed and moveable bundles in magnetizing bars of steel, as already described (97), fig. 63. With an apparatus of this kind, consisting of two separate magazines, each weighing about 20 lbs., and placed with their poles reversed, as represented fig. 61 (93), 100 lbs. is required to separate the keepers N T, P S, joining the opposite poles, and a common needle is magnetized to saturation by mere contact with either of the two projecting armatures.

108. M. Biot forms the armour of several plates of soft iron, which cover the elementary plates for some distance within their extremities, and terminate without in a trapezoidal form, the whole armature constituting one common mass, into which the bars are inserted.

Such combinations of bars in fixed and moveable bundles may be extended to other forms and numbers with advantage:

small bundles of six or eight bars, united about a projecting hexagonal or octagonal armature of soft iron at each end, form very convenient and available arrangements for general experiment. These combinations of several bars may be either bound together by metallic bands, as represented in fig. 68, or they may be united by screws passing through the bundles, the bars being previously drilled and fitted together for that purpose.

109. In combinations of bars of the horse-shoe form, represented in fig. 10, p. 15, and which for general purposes are the most convenient and perfect of any, the iron armatures are seldom applied; the separate pieces are screwed together at the centre, and a little within the poles, by means of holes drilled through the bars. The extremities or poles are rubbed to a perfectly even surface. Sometimes the successive bars, both in straight and curved magnets, are made to recede and back up the central piece on each side, like steps, leaving the poles of the central piece to project alone, as represented in fig. 9, p. 15.

A compound magnet of the horse-shoe form, consisting of six bars from 2 feet to 30 inches long, ·8 of an inch wide, and ·4 thick, and bent with a free curvature, so as to give a length of 10 or 12 inches from the shoulder to the pole on each side, will be found, when accurately fitted and screwed firmly together, and the polar surfaces rendered smooth and parallel, an extremely powerful combination. The curvature and form should be such as to give about 7 inches across at the shoulder, and allow of the polar extremities coming within an inch of each other.

Professor Barlow employed twelve bars, of about 15 inches in length, 1 inch wide at the centre, diminishing to $\frac{3}{4}$ths of an inch at the extremities, and $\frac{1}{4}$ of an inch thick: these were bent into the horse-shoe form, so as to give each side a length of about 6 inches. The bars were accurately filed, drilled, and fitted together, previously to being hardened and magnetized, and the extremities finally rubbed down with putty-powder.

This combination sustained from the hook of the keeper 40 lbs. Professor Barlow found, however, that a greater proportionate power might be obtained by means of bars of a greater length, or less proportionate width.

A very manageable and efficient compound magnet of the horse-shoe form may be derived by the employment of ten steel bars, each 25 inches in length, $\frac{7}{10}$ths wide, and $\frac{2}{10}$ths of an inch thick, bent so as to bring the poles within $\frac{4}{10}$ths of an inch of each other, the curvature being such as to give a length of about 10 inches in a vertical line from the surface of the keeper to the extremity of the centre of the curvature, which will be found to give a width of about $4\frac{1}{2}$ inches between the shoulders of the magnet.

The most powerful magnet of the horse-shoe form as yet produced was exhibited by Dr. Faraday at a meeting of the Royal Institution, in May, 1850. This magnet, although not weighing above 1 lb. avoirdupois, could sustain 26 lbs. suspended from the keeper. The power of one pole alone was such as to sustain an iron cylinder equal to the weight of the magnet, being at least twice the sustaining power expressed by Haecker's formula for magnets of this kind.

The bar constituting this magnet is about a foot in length, 1 inch wide, and three-tenths thick; the opening between the poles is about an inch, and the length of the axis within nearly 5 inches. The steel is not perfectly hard, but may be marked with a file; the face of the polar surfaces is ground very flat and fair, and the keeper very closely fitted.

This magnet was made by Logeman, of Haerlem, after the process of Mr. Elias.

110. It is quite essential in every magnetic combination, if we wish to preserve the accumulated force, that the bars or compound magnets be laid with their respective poles reverse to each other and united by soft iron keepers, as represented in fig. 61, (93). In the horse-shoe magnet the opposed poles are accurately placed by construction; it is only necessary in this case to apply the soft iron keeper.

The magnetic power of a single bar or needle will be effectually and best preserved by placing it in grooved rests of soft iron, fixed to the end of a light iron plate about the same width as the bar; it is thus retained in position and effectually preserved.

Sets of straight bars to be employed for general experimental purposes are usually laid together with reversed poles between small cheeks, fixed in a frame or neat wood tray, lined with red or blue cloth; a short bar of soft iron being placed directly across the dissimilar poles at each end, so as to effectually tie them together magnetically.

A set of eight or ten bars from 9 to 10 inches in length, $\frac{3}{4}$ of an inch wide, and $\frac{1}{4}$ of an inch thick, will be found very useful in magnetic researches. Mr. Canton employed smaller bars, in sets of twelve; these were $5\frac{1}{2}$ inches in length, $\frac{1}{2}$ an inch wide, and $\frac{3}{20}$ths of an inch thick.

111. In combining many bars, either straight or curved, so as to produce accumulative power, we are met by a somewhat serious inconvenience; the mutual repulsion of the similar poles is such that when many bars are set closely together, the proportionate power of the mass as a whole becomes greatly weakened, whilst the magnetism of many of the bars is not only very frequently destroyed, but their polarities become reversed. Scoresby has also fully investigated this question in his 'Magnetic Investigations,' and from these we derive the following results.

Any single bar or plate has more *proportionate* magnetic power than two such bars or plates conjoined.

A combination of bars or plates is always more powerful than any single bar containing the same quantity of steel in mass.

The *absolute gain* of power by each additional bar diminishes progressively, and hence a limit is attained to the extent of the combination.

112. With a view of avoiding the deterioration in magnetic power, from the repulsion of the similar poles on each other,

Scoresby was led, in compound magnets, to interpose discs of wood, card-board, or some non-magnetic substance, between the extremities of the bars, so as to keep them out of any very close contact: by this arrangement the accumulated power became more fully obtained. When 30 plates of tempered cast steel, 2 feet long, $1\frac{1}{2}$ inch wide, and about $\frac{1}{25}$th of an inch thick, were fully magnetized, and combined and separated by $\frac{1}{2}$-inch spaces, the resulting compound magnet had at least twice the magnetic energy which the same plates exhibited in contact.

113. The most favourable conditions for the construction of compound magnets, are, a similarity of quality and form in the steel, both as to mass and dimensions, and a similarity also in temper: the spacing out or separation of the similar poles by a disc of some intervening non-magnetic substance, and the employment of comparatively thin plates at a high temper, which last appears essential to retentive power, is likewise requisite. Scoresby found that in the construction of a compound magnet of thin plates of steel busk, or other steel plates of commerce, at a spring temper (87), the accumulated power very soon approached a maximum, so that not above 24 plates, in sets from 15 inches to 2 feet in length, and $\frac{1}{20}$th of an inch thick, could be usefully combined; whereas, with the same plates rendered very hard, above 192 plates might be effectually combined, and with a result exceeding by five or six times the combined power of thicker bars commonly employed for compound magnets.

The temperament of bars, however, for combinations of the horse-shoe form, appears to admit of considerable variation from that of combinations of the straight bar form. In fact, the annealling or tempering which appears to detract from the combined energy of plates or straight bars, improves, up to a certain extent, the combination of curved bars: this may probably arise from the circumstance of the proximate position of the opposite poles, by which the deterioration of the similar poles by their near contact is to a certain ex-

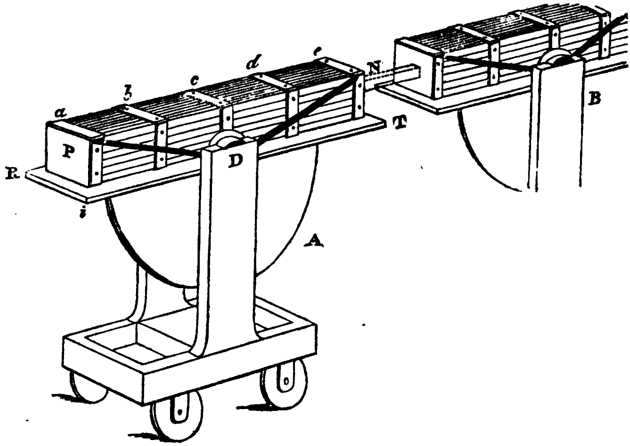
tent parried, the opposite elements tending to strengthen each other.

114. *Magnetic powers of cast iron.*—The fusion and running of iron into various forms, especially thin bars and plates, by which it is exposed to a greater or less degree of carbonization and a rapid cooling, may be considered favourable to the retention of magnetic energy. It is hence found not ill adapted to the purpose of artificial magnets, although far beneath the powers of properly tempered steel. Cast iron may, in fact, be considered in its magnetic conditions as intermediate between steel and common soft iron: when cast into hard thin bars or plates, it is capable of receiving a high magnetic condition, and it may consequently be advantageously employed for permanent magnets, especially in cases in which economy is an object, the expense of cast-iron plates being extremely small as compared with plates of the best steel. Iron of the very best quality appears to possess the greatest retentive power.

115. *Magnetic Machines.*—When a very extended series of magnetic bars are associated together systematically, in such a way as to constitute one great and massive whole, such a combination has been termed more especially a magnetic machine. The celebrated Dr. Gowan Knight, F. R. S., first originated a machine of this kind, his object being an immediate and intense development of power in steel needles by a simple contact with the poles of such an instrument. Dr. Knight's machine was constructed about the middle of the last century. It consisted of two great magazines, A B, fig. 70, comprising in all 480 bars, each bar 15 inches in length, 1 inch wide, and ½ an inch thick: these bars were disposed, in the respective parts A, B, in four lengths, *a b*, *b c*, *c d*, *d e*; these were made up of 60 bars, arranged in 6 beds or courses of 10 bars each, set edgewise, so that he had in breadth 10 bars and in depth 6 bars,—in all, 60 bars. This, repeated through *a b*, *b c*, *c d*, &c., gave a total of 240. All the north poles were turned the same way: the dissimilar poles, therefore, were

brought into contact; and in order to press the joints of the bars closely together, an iron plate was placed over the ends of the system, as at P N, perforated with 60 holes for screws: the screws could be turned up against each respective length of bars, the plates being held together by the braces D P, D N.

Fig. 70.



The buts or joints at *a b c d* fell under brass braces, which admitted of being set tight upon the bars by binding-screws. Finally, two thick plates or armatures of iron P N were placed over the ends of the poles of the series,—and thus the whole became bound firmly together, forming one great magnetic combination.

As each of these magazines A B weighed 500 lbs., it became requisite to mount them in such a way as to admit of their being easily handled and placed in any position relative to each other. To effect this, each magazine was placed on a stout mahogany board, R T, moveable on central gudgeons at D upon two vertical standards, made to turn on an axis, like the trunnions of a cannon, and remain easily in any position: to assist

this operation, a strong semicircular piece of mahogany was fixed to the plank R T, so as to revolve between the standards, as indicated in the figure. The two magazines, thus mounted, were finally set on four wheels, by which they could be readily moved into any required position.

A small bar of hard steel, N P, placed between the opposite poles N P of the magazines, became instantly magnetic. This machine is still in the possession of the Royal Society, but has evidently undergone some subsequent changes; the magazines are now enclosed in cases of wood, furnished with projecting armatures of solid parallelopipeds of iron, 1 foot high and 2 inches wide: the internal construction, however, remains apparently unchanged.

The power of such large combinations of artificial magnets is not found, for the reasons already given (111), commensurate to the extent of the system. We have not any authentic record of the actual power of Dr. Knight's machine in his time. Faraday tried it, however, in its present state, about the year 1830, and found that when a soft iron cylinder 1 foot long and $\frac{3}{4}$ of an inch in diameter was placed across the dissimilar poles of the two magazines, it required a force of about 100 lbs. to break down the attractive power.

116. There does not appear to be any common standard of reference for the comparative weights and lifting power of artificial magnets, the supporting powers of some magnets, as regards the weight of steel, being much greater than others. Haecker, who carefully investigated this question, gives, however, for the sustaining power of artificial magnets, the following formula:

$$\tfrac{2}{3}\,W \times 10{\cdot}233.$$

That is to say, the cube root of the square of the weight, multiplied by a certain constant. This comes near the general experimental result. In the case, however, of the magnet before described (109), Haecker's formula was greatly exceeded.

INSTRUMENTS FOR INDICATING THE PRESENCE AND DETERMINING THE POLARITY OF MAGNETIC FORCES, AND MEASURING THEIR QUANTITATIVE POWER UNDER VARIOUS CONDITIONS.

117. Instruments for indicating the mere presence of magnetic force, and determining its peculiar polarity, may be termed, as before observed (30), magnetoscopes: those for its quantitative measurement, under various conditions, may be considered as magnetometers.

Magnetoscopes generally consist of light bars or needles, either suspended by a delicate flexible thread, or attached to an agate or metallic cap, and set on a fine central point. Of these two forms of suspension, the filar suspension is unquestionably the most sensitive. The Rev. A. Bennet, F. R. S., employed filaments of a spider's web, which proved so extremely delicate, that two small pieces of straw, placed at right angles to each other, in the form of the letter T inverted, would, when thus suspended under a closed receiver, turn toward a person coming within 3 feet of the glass, and would move so decidedly toward wires merely heated by the hand, as much to resemble magnetic attraction. A fine and weakly magnetic steel wire, suspended from a spider's thread of 3 in. in length, would admit of being twisted round 18,000 times, and yet continue to point accurately in the meridian,—so little was the thread sensible of torsion.*

118. The suspension of magnetic needles, however, by so fragile a thread requires a somewhat dexterous and practised hand. Mr. Bennet was in the habit of catching the thread between the expanded branches of a forked twig, and then fixing it to the needle and to the wire of suspension by means of a little quick-drying glutinous varnish. A more generally applicable method, however, is to lay each end of the thread,

* Phil. Trans. for 1792, p. 86.

whilst on the fork, across a thin slip of paper, having previously smeared the paper with a little quick-drying cement of any kind. We thus provide for a ready intermediate attachment of the thread, both to the needle and point of suspension.

An extremely light suspension, not so difficult as the former, consists of a single filament from the thread of the silk-worm: this may be managed in a similar way. For less refined purposes, coarser filaments may be employed, and their ends, by a little practice, easily tied into loops. We may also employ occasionally filaments of very fine flax, cotton, and the human hair.

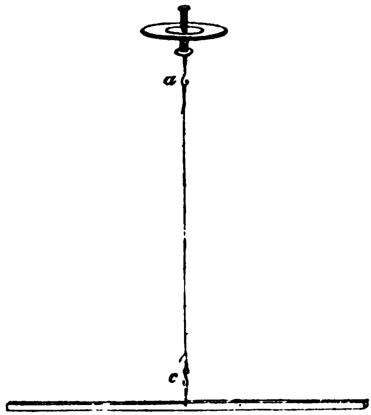
119. In many cases it is desirable to terminate the extremities of the suspension in small open loops: such loops may consist of slight sewing silk, waxed, and secured by paste, or some other cement, to the paper slips, the paper coming between the extremities of the silk: the ends of the silk may be touched with a little common varnish, glue, or gum, and pressed between forceps close to the paper. Loops of thin silver or copper wire, flattened at their ends, may be affixed to the paper in a similar way. These loops admit of further attachment to magnetic bars or needles, and to a point of suspension by intermediate light double hooks of fine wire. A variety of extemporaneous methods, however, will occur to the experimentalist whilst engaged in this kind of manipulation: needles may occasionally be fixed to a thread of suspension by a direct application of the thread to the needle by a little easy cement, such as bees'-wax.

120. A small stirrup, formed by a light plate of copper or silver, has been sometimes attached to the lower extremity of a suspension thread, for the reception and retention of any needle or bar we desire to employ: this method was adopted by Coulombe. It is, however, generally more accurate to fix the thread to the centre of the needle itself. Light needles or bars are best managed in the following way: Let a very fine central vertical hole be drilled through the edge of the bar into

a hole drilled transversely to the bar, and passing also through the centre, as before described (21); the bight of a fine silk loop may then be readily passed up through the central vertical hole, and secured within the bar by a common knot. We may now suspend the bar from the loop of the suspension thread by an intermediate small double hook.

The annexed figure, 71, represents a light bar thus suspended, in which *a c* is the thread of suspension, and *c* the double hook connecting the loops of the thread and bar. Very small double metallic forceps, with compressing rings, or a cleft wire or piece of wood, will be sometimes useful in suspending magnetic bars and needles: in this case the small paper slips terminating the suspension are placed between the forceps.

Fig. 71.



Every thing, however, connected with the suspension should be as light and delicate as it is possible. Small suspension hooks are easily turned up from fine copper or silver wire by means of round forceps.

121. The usual method of suspension on a fine central point is by means of an agate or metal cap, secured to the centre of the bar or needle. In applying these caps for refined purposes, a hole should be drilled through the needle or bar, which, if required, may be flattened out at the centre, and an agate cap, or a small fragment of flint, secured directly over it by a little cement of shell lac. Where the size of the bar admits, the agate may be mounted in a ring of brass or silver, and screwed into the needle, the needle being duly formed and prepared at

its centre for receiving it. Caps of hard metal may be soldered to small needles or bars, or otherwise applied in a similar way, by insertion into the bar itself.

When needles are employed extremely slight and thin, they may be curved in the middle, as in figure 72, and then mounted on a hard centre *c* of glass, flint, agate, or metal, by means of a descending fine point v, soldered or otherwise attached to the vertex of the curved portion, and so as to bring the centre of gravity of the system just beneath the point of suspension.

Fig. 72.

122. The Chinese have a very ingenious method of suspending a magnetic needle, which is at once delicate and effective. A small bent slip of brass, *d c e*, fig. 73, carrying a light ring at its vertex *c*, is attached to a small conical cap *d e*, made of very hard metal: the legs *c d* and *c e* of the brass project a little beneath the cap, and are secured to the cap by fine holes drilled through its sides. The needle, *n c s*, to be suspended, and which is seldom more than an inch in length and $\frac{1}{40}$th of an inch in diameter, is secured in the ring *c*, and the whole mounted on a fine point of support.

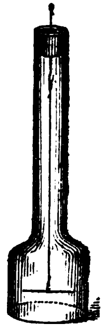
Fig. 73.

In this arrangement, notwithstanding that the needle is above the point of suspension, yet the centre of gravity of the three parts of the system, viz. *n c s*, *d c e*, and *d e*, falls below that point.

123. *Magnetoscope of simple suspension.*—This consists of a short fine magnetic needle, from $\frac{1}{2}$ an inch to 1 inch in length, and from $\frac{1}{30}$th to $\frac{1}{50}$th of an inch in diameter: it may be made of good piano-forte wire, brought to a spring temper. The north side of it should be coloured with a little vermilion. It may be suspended by any of the methods just described, and placed within a common lamp-glass, to shield it from currents of air. If the filar suspension

be employed (117), the filament may be about 4 inches in length, and should be attached to a metallic rod, moveable with friction through a stopper of fine cork fitted in the upper end of the glass, so as to admit of being raised or depressed through a given space, as shown in the annexed figure 74. Bennet's magnetoscope, with the spiders' web suspension, may be managed in this way.

Fig. 74.



These simple instruments are very applicable to experiments on induction, such as already described (33 and 57), and in which the play of the needle should be sensible and manifest.

Magnetoscope needles of greater length and magnitude should be similarly treated, using larger filaments when requisite. If the exhibition of attractive force, without the interference of polarity, be required, soft iron needles may be substituted for the magnetic needles, as in the cases alluded to. (57.)

Wheatstone's method of exhibiting small forces by means of short steel needles standing in an erect position on the pole of a powerful magnet (55), constitutes a very delicate form of magnetoscope, especially available in certain investigations.

The arrangements represented in figures 37 and 38, p. 45, may be considered as magnetoscopes of a peculiar kind, applicable to the combined operations of magnetism and Voltaic electricity.

MAGNETOMETERS.

124. The quantitative measurement of magnetic forces may be either direct applications of equivalent weight, or any species of equivalent reactive power, as in the reactive force of torsion; or may consist of indirect determinations of force, through the medium of certain relative effects, as in the amount of deviation of a suspended magnetic needle from its line of

direction by the influence of a magnet placed at a given distance from the needle.

125. *Scale-beam Magnetometer.*—The common scale-beam has been occasionally applied to the measurement of magnetic forces. A small cylinder of iron or a magnet is to be suspended from one arm of the beam, and counterpoised by weights in a scale-pan suspended on the opposite arm. The beam being sustained on any convenient support in the usual way, a second magnet or iron is placed on the table, immediately under this, and the attractive force at any given measured distance is estimated by additional weights placed in the scale-pan.

Much care is requisite in effecting this experiment. The beam should not be allowed any very considerable play, but be limited in its motions by two vertical forked stops, one under each arm. If the beam, with a given added weight in the scale-pan, be overset by the attractive force, and rest on the stop, we may either increase the distance of the attracting bodies, or increase the weight, so as just to catch the instant of the balance of the force. Or, supposing a given added weight in the scale-pan, we may continue to approximate a magnet toward the suspended iron or other magnet over a divided scale of distance, and catch the point at which the beam turns.

The bent lever, or any self-adjusting balance, may be also employed in a similar way to the measurement of magnetic force.

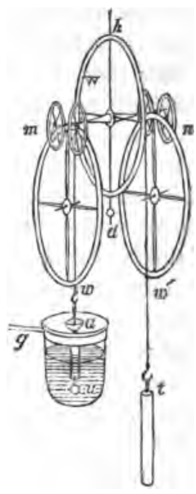
Of this class of magnetometer the simple contrivance represented in figure 29 (37) is perhaps the best adapted to refined investigations, being at the same time very applicable to the exhibition of elementary magnetic phenomena, especially the phenomena of induction. We have only to find by small weights placed on the suspended cylinder *n* the value of the degrees of inclination of the beam, and we may refer the force in operation to a fixed standard of weight. The range, how-

ever, is limited to the degree of inclination which the beam can support without oversetting.

126. *The Hydrostatic Magnetometer.*—This instrument, shown in its general form in the frontispiece, fig. 76, and partially explained in the annexed and following figures, is of such convenient and universal application to the measurement and exhibition of elementary magnetic phenomena and forces, that a particular description of it appears essential.

A light grooved wheel, w, fig. 75, about 2 inches in diameter, being accurately poised on a firm axis, *m n*, is mounted on the smooth circumferences of two similar wheels, *m w*, *n w'*. The extremities of the axis *m n* are turned down to fine long pivots, and whilst resting on the friction-wheels *m w*, *n w'*, pass out at *m n* between other small check-wheels, two at each extremity of the axis, so that the wheel w cannot fall to either side: great freedom of motion is thus obtained. These friction and check wheels are set on points or pivots in light frames of brass, and the whole is supported on short pillars screwed to a horizontal plate or stage, as shown in the frontispiece, A B, fig. 76. The stage is sustained on a vertical column, A E, fixed to an elliptical base of mahogany, E, supported on three levelling screws.

Fig. 75.



There is a short pin *h*, fig. 75, fixed in the circumference of the wheel w, to receive an index of light reed, cut to a point, and moveable over a graduated arc M N, placed behind the wheel, as represented in the frontispiece: the weight of this index is balanced by a small globular mass *d*, moveable on a screw in the opposite point of the circumference; so that the wheel alone with the index would rest in any position, or nearly

so. The arc M N is a quadrant divided into 180 parts,—90 in the direction I M, and 90 in the direction I N, the centre 0 being marked zero. Two fine holes are drilled through the wheel, one on each side of the point *h*, for receiving and securing two silk lines, *w w'*: these lines pass over the circumference on opposite arms of the wheel, and terminate in small hooks, *t* and *w*. A cylinder of soft iron *t*, or a small magnet, rather less than 2 inches in length and ¼ of an inch in diameter, is suspended by a silk loop from one of these lines, *w'*, and a cylindrical counterpoise of wood, *a u*, weighted at *u*, and partly immersed in water, is hung in like manner from the other line, *w*. The weights, and altitude of the water, and of the vessel *q* containing it, are so adjusted, that when the whole system is in equilibrio, the index *b o* is at zero of the arc M N. With a view to a perfect adjustment of the index, the water-vessel *q* is supported in a ring of brass at the extremity of a rod *q*, moveable in a tube *k*, fig. 76: this tube is attached to a sliding piece *b h*, acted on by a milled head at *h* and a screw within the cylinder, which is fixed to the stage A B,—so that the water-vessel may be easily raised or depressed by a small quantity, and thus the index be regulated to zero of the arc with the greatest precision; for it is evident, by the construction of the instrument, that the position of the index will depend on the greater or less immersion of the cylindrical counterpoise *a u*, the weight of which being once adjusted to a given line of immersion, and a given position of the wheel W and index O, any elevation or depression of the water-vessel *q* must necessarily move the wheel. The counterpoise *a u* is about 1½ inch in length and full ·3 of an inch in diameter: a small ball of lead is attached to its lowest part, in order to give it a sufficient immersion, and at the same time balance the iron cylinder *t* when the float is about half immersed in the water. With a view to a final regulation of the weight, a small hemispherical cup *a* is fixed on the head of the counterpoise for the reception of any further small weights required. This counterpoise is accurately turned out of fine-grained ma-

hogany, and is freed from grease or varnish of any kind, so as to admit of its becoming easily wetted in the water.

The column A E supporting the stage A B consists of two tubes of brass, one, G, moveable within the other, E C, so that by a rack on the sliding tube G, and a pinion on the fixed tube at C, the whole of the parts just described may be raised or lowered through given distances, as shown by a divided scale G, adjustable to any point by means of a slide and groove in the moveable tube G. The brass tubes composing the column are each about a foot in length and an inch in diameter.

(127.) It will be immediately perceived, from the general construction of this instrument, that if any force cause the cylinder *t* to descend, then the index *h o* will move forward in the direction O N, until such a portion of the counterpoise *a u* rises out of the water as is sufficient to furnish, in the fluid it ceases to displace, an equal and contrary force. In like manner, if any force cause the cylinder *t* to ascend, then we have the reverse of this,—the counterpoise obtains an equivalent increased emersion, and the index moves in the opposite direction, O M. Thus if we place a weight of 1 grain, for example, on the iron cylinder *t*, the index will indicate, in the direction O N, a given number of degrees equal to a force of 1 grain. If we double this weight, we obtain a force of 2 grains, and so on. The converse of this arises on placing the weights in the cup of the counterpoise *a u*. We may thus reduce the indications to a known standard of weight. It is further evident, that, whether we operate on the system by gravity or by the attractive or repulsive force of a magnet, the indications of force are equally true.

If the instrument be well constructed, and the counterpoise freely wetted in the water, the march of the index in either of the directions O N or O M will correspond to the added weights. Thus, if 1 grain gives 3 degrees, 2 grains will give 6 degrees, and so on. And thus we obtain a continual and known measure of the force we seek to examine, within a given range of degrees of the arc, which will be more or less extensive ac-

cording to the dimensions of the cylindrical counterpoise, the intensity of the force, and the rate of its increase. When we require to examine very powerful forces, or forces operating on the suspended iron *t* at small distances, it is requisite to increase the size of the counterpoise float, the indications of which we may always find the value of in grains, as before.

Previously to suspending the cylindrical counterpoise *a u*, the iron cylinder *t* should be placed in equilibrio on the wheel W, with an equal and opposite weight, as previously determined by an accurate scale-beam, in order to observe if, when loaded with the whole, the wheel W and index are indifferent as to position on any part of the arc, or nearly so. The instrument will be sufficiently delicate, if, when loaded in this way with 350 grains, it is set in motion by something more than $\frac{1}{2}$ a grain added to either side.

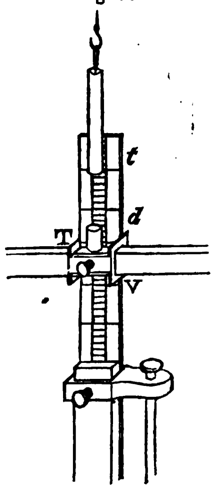
In order to retain the wheel W, figs. 75 and 76, in its position at the time of removing either of the suspended bodies, a small brass prong is inserted at *h* into the arms of the circular segment M N, so as to enclose the pin *h* carrying the index: the wheel is thus prevented from falling to either side.

128. The forces requiring to be measured are brought to operate on the suspended cylinder *t* through the medium of induction on soft iron, or by a magnetic bar placed immediately under it, either vertically or horizontally. In the vertical arrangement, shown in the frontispiece, the magnet or iron is fixed against a graduated scale S, by which the distance between the attracting surfaces or bodies is estimated. This scale, together with the magnet H, is secured by light bands *s*, of brass, united by a rod D K. The lower band and rod D are both fixed to a stage D, moveable between guide-pieces, and acted on through a nut at *q* by a vertical screw P *q*, about 6 inches in length and $\frac{3}{8}$ths of an inch in diameter; so that the whole may be raised or depressed, and hence the suspended cylinder and magnet placed at any required distance apart. The regulation of this important element in the operation of magnetic forces is hence provided for in two ways, viz. by the

rack at G and the milled head at P, either of which may be employed, as found most convenient. The scale s is of box-wood, 1 foot in length, ¾ of an inch wide, and ¼ of an inch thick: it is divided into inches, subdivided into tenths and twentieths of an inch. About 6 inches of the upper part is divided in this way, viz. 3 inches on each side of a central division, which is marked zero; the rest of the piece extends to the stage D. The magnetic bar H is tied to the scale by compressing screws and simple brass bands, either fixed, as at D and K, or moveable, as at H. This adjusting apparatus is secured to a stout brass plate R, fitted by a dovetail into a sliding piece *v*, forming part of the mahogany stand E, so that it may be removed at pleasure. The brass bands and frames at D H K are sufficiently capacious to enclose two bars together if required, the superabundant space being filled when only one magnet is employed, either by a bar of wood or small wedge pieces in the brass frames.

129. When we require to examine the forces in different points of a moderate sized magnetic bar, as exemplified in Exp. 11, page 21, the bar is laid in a small frame-piece T V, fig. 77, temporarily fixed by a compressing screw to the divided scale s, in the way already described, the force on the suspended cylinder *t* being caused to operate through a small cylinder of soft iron *d*, accurately fitted to the surface of the bar; and thus, by sliding the bar along in the holding frame, we may get, approximatively, by induction on the iron *d*, the force of any point in the bar.

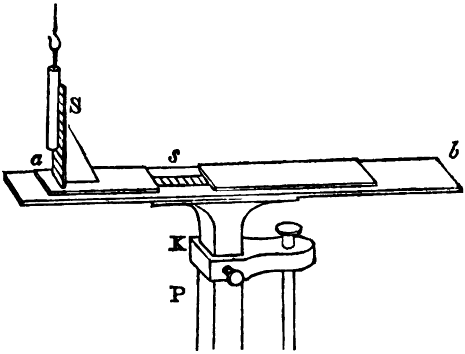
Fig. 77.



When the bar is of considerable magnitude and weight, or we require to examine inductive forces, such as in Experiments

19, 22, 23 (pages 29, 32, 33), the magnets may be placed on a narrow table, *a b*, fig. 78, supported on a central square pillar P, fitted to the frame-pieces, K P, of the adjusting appa-

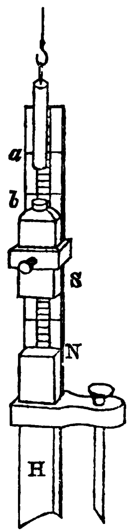
Fig. 78.



ratus already described (128), so that the whole may be raised or depressed through any given distance. In this case the divided scale S, fig. 78, which measures the distance *a* between the attracting or repelling surfaces, is a detached piece fixed against one of the perpendicular sides of a right-angled triangle, so as to be any where placed upright on the bar: the table *a b* also has a divided scale *s*, moveable in a wide groove through its centre, by which any distance, *s*, between magnetic masses may be also shown. When the bars are very ponderous, two supports are required, one at each end of the table *a b*.

130. Inductive forces are examined vertically by fixing the masses by compressing bands *s* against the scale S, fig. 78, as represented in the annexed fig. 79, and of which we may have, if requisite, two or three in succession.

Fig. 79



These arrangements put us in a position to note readily and simultaneously all relative distances and forces under a great variety of magnetic and apparently complicated conditions. In the arrangement, fig. 79, for example, we may fix a mass of iron S, at successive distances, S N, from a magnet H, and yet preserve the distance, *a b*, at which the induced force operates constant, either by the rack and pinion C, or the milled head and screw P R, fig. 76, and thus arrive at a measure of the inductive force on the intermediate mass, S.

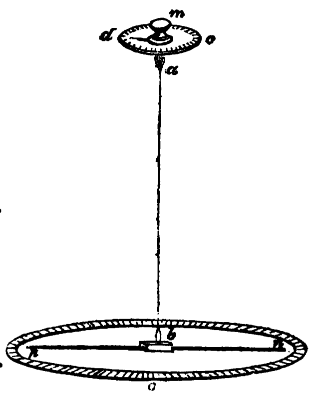
131. We have been somewhat prolix in our description of this instrument, but not unnecessarily so. There is scarcely any elementary experiment in magnetism which it does not completely and satisfactorily illustrate, besides furnishing quantitative measures of great importance to the mathematical inquirer into the laws and operations of magnetic force. The experiments given in pages 21, 27, 28 to 36, may be all repeated with this instrument, only varying the operation of the forces, which are to be referred to the suspended body *t*, and which may be either soft iron or a magnet, as the case requires. Thus, on suspending a small and powerfully permanent magnetic cylinder, and sliding a long bar under it at a constant distance, we have all the attractions and repulsions shown by the march of the index in opposite directions, O M, O N, fig. 76 (frontispiece). In employing a cylinder of soft iron, we observe the precise position of the points of greatest and least attraction, the centre and poles of the bar, as already explained (25).

132. *Torsion Balance.*—This species of magnetometer is derived from the reactive or untwisting force of a fine wire when subjected to a certain amount of torsion. The principle was first applied by the Rev. J. Michell, F. R. S., about the year 1790, for rendering sensible the attractions of small quantities of matter. His apparatus was employed by Cavendish, in 1798, after Michell's death, in his experiments to determine the density of the earth.* Coulombe

* Phil. Trans. for 1798, p. 469.

further adopted the same principle, under the form of what is termed 'the balance of torsion.' In this instrument, the directive or other force acting on a magnetic bar or needle *p n*, fig. 80, is balanced against the twisted force of a fine wire *a b*, suspended from a point of support *a*, and to which the needle or bar is attached, the point of support being the terminating extremity of a vertical wire or rod, *m a*, passing through a collar in a plate *d m c a*, and surmounted by a milled head *m*. It is here evident, that by turning the milled-head *m*, we necessarily turn round the wire *a b*; and if the bar or needle *p n* resist this twist, we may place the resisting force in equilibrio with the reactive force of the torsion; or if, on the contrary, we apply a force to either pole of the needle *p n*, considered as a lever, then the wire *a b*, resisting the movement of the needle by the torsion impressed upon it, furnishes a balance to the force in a similar way. The amount of twist given to the wire is estimated in degrees, either by a graduated circle, *p b n o*, within which the bar or needle turns, or by a graduated plate, *c m d a*, with an index *c*, showing by how many degrees the point *a* has been turned round, and consequently the twist impressed on the wire *a b*. Thus Coulombe found, for example, that with a fine wire about 30 inches in length it was requisite to turn the index *c* through 35 degrees, in order to force a magnetic needle *p n*, 24 inches long and about the $\frac{1}{10}$th of an inch in diameter, through one degree of the circle *p b n o*, that is, to deviate one degree from its line of direction; and thus a comparative value of the directive power at one degree was obtained.

Fig. 80.

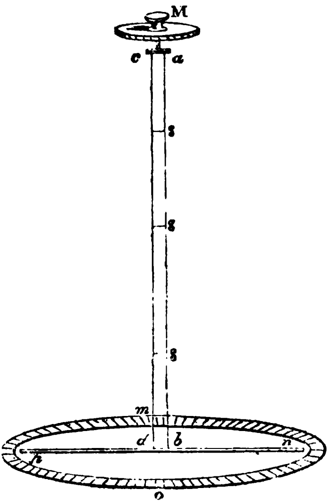


In this instrument the needle *p n* is fixed in a small stirrup *b*, and is enclosed in a glass case, the plate *c d* and wire *a b* being supported in a tube of 30 inches in length, raised from the centre of the frame-work of the case.

Coulombe has shown that the reactive force of the wire *a b*, when subjected to a moderate twist, is directly proportionate to the sine of the angle or arc through which the extremity *p* of the needle has moved, and is not affected by the weight of the suspended body.

133. *The Bifilar Balance.*—In this magnetometer a reactive force is derived from the gravity of a needle *p n*, fig. 81, or other body, suspended centrally by two parallel threads, *a b*, *c d*, from a short cross-wire *c a*, and which can be moved round so as to cause the threads to turn as it were upon each other, by which the mass of the needle *p n*, if resisting the twist, is insensibly raised, and its gravity or weight thus made to balance any given force operating on it; or, supposing the needle *p n* to be at rest on the magnetic meridian, when the two threads of suspension are vertical and parallel, and it be caused to deviate from this position by the operation of a repulsive force on one of its poles *p*, then the two threads, *a b*, *c d*, will become more or less oblique to each other, and the needle will be raised by a small quantity, and the tendency of the needle to descend by gravity will be in equilibrio with the force acting on the poles of the needle, considered as a lever. Similarly, by turning the cross-wire *c a* by means of the micro-

Fig. 81.



meter M, through any number of degrees, we tend to turn the needle *p n* from its line of direction, and so twist the threads upon each other in a similar way, the directive force of the needle may be thus estimated. The other arrangements are similar to fig. 80.

The reactive force in these bifilar suspensions is directly as the distance between the threads and inversely as their lengths. It is also directly proportionate to the weight of the needle or other suspended mass, and is as the sine of the angle of deflection of the needle.

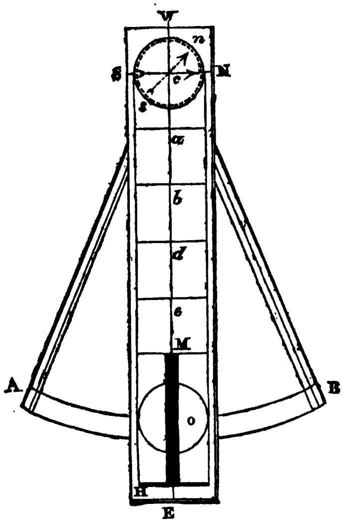
To prevent the threads from collapsing upon each other, small stays *s s s* of light cork or reed are inserted at given distances between the threads.

The bifilar suspension was first employed by the author in the year 1831: the principle was communicated to the Royal Society in 1832, as may be seen by a MS. letter to Professor Christie in the archives of the Royal Society. It was further made known through the medium of the Royal Society of Edinburgh in 1833, as appears by the 13th volume of the Society's Transactions, and in 1835 was laid before the Physical Section of the British Association, under the form of a Bifilar Balance.* The instrument is very fully and completely described in the Transactions of the Royal Society for 1836; and the same principle has been since resorted to in the Magnetic Observatories at Greenwich and other places, for estimating small variations in the directive force of a suspended magnetic bar.

134. *Magnetometer of Declination.*—This instrument consists of a light short needle, fig. 82, delicately suspended within a graduated ring of card or metal *s* S *n* N. The needle and divided circle are fixed in the axis, and near one extremity of a straight mahogany board E W, moveable about a point *c*, concentric with the centre of the needle, so that it may be readily turned for a short distance to either side of an arc A B, forming a base of support.

* British Association Reports, vol. iv. p. 17.

Fig. 82.



A central or axial line W E is drawn on the board, and another line S N at right angles to this, passing through the centre *c*. Other lines, *a b d*, &c., are drawn on the board parallel to S N, denoting the distance in inches of the points *a b d* from the centre of the needle.

The whole apparatus is so placed as to make the needle *c* coincident with the line S N, which may be finally and completely effected in turning the board E W a little to the right or the left upon the centre *c*. This adjustment complete, the axial line E W will be in an east and west direction, being at right angles to the meridional direction S N of the needle.

The force of a magnetic body M is estimated by placing it at a given distance M *c* from the centre of the needle, immediately in the axial or east and west line of the board E W, and at right angles to the direction S N of the needle, and noting the angle of deviation of the needle in degrees of the graduated circle *s* S *n* N. If the force of a magnet, M for example, be examined in this way at a distance M *c* from the centre of the needle, of five or six times the length of the needle, then the tangents of the angles of deviation of the needle, as found in the ordinary Mathematical Tables, afford a very fair approximative measure of the force or power of the bar. Thus, if the angles of deviation caused by two magnetic bars, whose separate powers we wished to determine, were at the same distance M *c*, 12 degrees and 40 degrees respectively,—then the relative

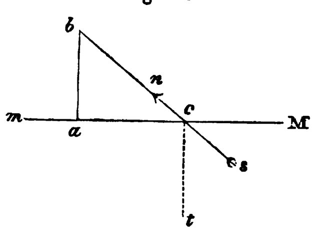
forces, as found in the column of tangents for these angles, would be as 2125 to 8390, or as 1 : 4, very nearly.

If the needle *c* were indefinitely short in respect of the magnet M, or the distance M *c* indefinitely great, then the force operating on the needle would be exactly measured by the tangent of the angle of deviation; but since we cannot employ a needle indefinitely small, or distances indefinitely great, we cannot realize in practice an absolutely perfect result. The errors, however, diminish rapidly with the distance; in fact, the force is not really exerted in the direction M *c*, but more or less obliquely on either side upon the arms of the needle. The power also of the magnet is not the same in the deviated position *s n* of the needle as in the rectangular position S N; hence, if we examine the force at small distances from the needle, certain corrections will be requisite, tending to complicate the experiment, but which diminish rapidly as the distance is increased.*

For the purpose of convenience and accurate observation, the magnetic bodies whose forces we require to examine are placed on a circular plate O, moveable about a centre O, on a short rectangular board H M beneath. This last board moves between guide-pieces on the board E W, so as to admit of the

* Let *n c s* in the annexed fig. 83 represent a magnetic needle deviating from the magnetic meridian M *c a* by a force acting in direction *t c*, as in fig. 82. Take *c a* to represent the horizontal or directive force of *n s*; draw *a b* perpendicular to M *m*, meeting *s n* prolonged in *b*; then we have *a b* as representing the deflective force operating in direction *t c* as before. But in this triangle *c a b* we have, by the principles of trigonometry, *c a* : *a b* :: rad. : tangent of *a c b*. If horizontal force *c a* be called unity, or 1, we have *a b* × R = tangent of the deviation *a c b* × 1 or directive force = tangent of deviation, R being also considered as unity.

Fig. 83.

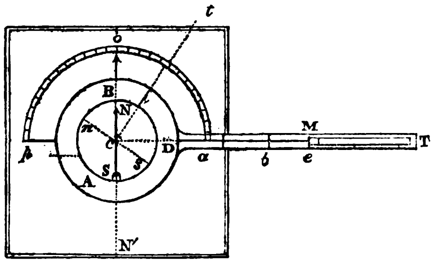


magnetic body M being set at any required distance from the needle S N, whilst by the revolving circular plate O we are enabled to reverse the position of a magnet M without deranging its position, and so examine the force of the opposite pole.

The precise situations and directions being once obtained, the respective moveable parts are fixed by appropriate screws and clamps.

135. *Magnetometer of Deflection.*—This instrument, represented in the annexed figure 84, is very similar to the

Fig. 84.



former in principle; the difference being in the position of the magnetic body under examination, which is always placed at right angles to the direction of the deflected needle. In this figure S N is a delicately suspended needle, with an accurately divided circle or card *c*, by which its angular deflections from the magnetic meridian are shown. The needle and card are supported on a fixed point or centre *c*, so as to be a little raised above a circular disc of mahogany A B D, concentric with this needle, and which is moveable about the central point *c*, immediately under it.

The circular disc A B D carries a long projecting arm D T, in the direction of a diameter of the circle; an axial line D T, is drawn upon this arm, which, if continued, would pass through the centre *c*, immediately under the centre of the needle. This line is divided, as in the former case, fig. 82, by other transverse lines *a b e*, showing the distance of these

points from the centre *c*. The whole is placed on a firm mahogany base or clamped board, furnished with a divided semicircular arc *p o a*, concentric with the graduated circle of the needle. This arc is divided on each side of the centre *o*, up to 90°, the point *o* being the zero of the arc. By means of a light index B *o*, attached to the moveable circle A B D, we are enabled to estimate, on a large scale, the angular quantity through which the circle has been turned either way.

The instrument being adjusted so as to bring the line D T perpendicular to the direction of the needle or magnetic meridian N *o*, and the index B *o* at zero of the arc *p o a*; then the force of any magnetic body M T is measured, in placing it in the line D T, at a given distance C M, from the centre of the needle S N: in this case the needle will stand more or less oblique to the line of the deflecting body M, and will assume some other direction, *s n*. We now proceed to turn the circular board A B D and arm D T, in either direction, until we again bring the line of deflection at right angles to the new direction of the needle. Thus, when the new direction becomes *s n*, the line of deflection should be in the direction *t c*: now the angular quantity by which the arm D T has been turned, in order to establish the equilibrium in this precise position, corresponds to the angular deflection of the needle, that is, to the angle *n c* N, and this angle therefore becomes measured on a large scale *a o p*, by the index B *o*, however small a needle, S N, we may find it convenient to employ. Now the force of the deflecting body M T, if the distance *c* M be many times the length of the needle, will be very nearly as the sine of the angle of deflection as given in the ordinary Mathematical Tables.

Thus, if two magnets placed at the same distance *c* M from the centre *c*, or the same magnet placed at different distances, cause deflections of 20 and 43 degrees respectively, then the relative forces will be as 3420 and 6819, or as 1 : 2, very nearly.

136. In experiments of this kind the needle N S may be

considered as a pendulum, which, when drawn aside from its natural position, tends to return to it; and if by any equivalent statical force acting in a given direction we maintain the pendulum in any other position at any given angle to its natural position, the amount of such statical force, as is proved by mechanics, will vary with the sine of the angle of deviation. The conditions, however, of a magnetic needle, considered in this way, and sustained at a given angle to its meridian by a deflecting magnetic force, are both in this and the preceding case, fig. 82, extremely complicated and troublesome. The force which we measure is actually the resultant of all the forces of the magnet, and we have necessarily to consider it as proceeding from four elementary actions, two attractions and two repulsions; that is to say, the repulsions of the similar and the attractions of the dissimilar polarities (14). We must hence endeavour to place the experiment under such practical conditions as will enable us to consider the result as derived from a central force operating upon the poles of the needle in a given direction. In fig. 84 we have supposed the force to be directed from one pole of the deflecting magnet, M, in a direction always perpendicular to its actual position; still in this, as in the former instance, fig. 82, the forces are not really so exerted; they fall more or less obliquely to the needle upon each side of the centre, and it is only when the needle is supposed indefinitely short, or the distance C M, fig. 84, indefinitely great, that we can really consider these oblique forces as perpendicular to the line of the needle. We may, however, so consider them for most practical purposes, when we make the distance C M exceed five times the length of the needle, whilst the opposite pole T of the bar being still farther removed, the forces from this pole may be so far neglected. In this way we may arrive at very fair and valuable approximate measures.*

* Let S N, fig. 85, be a magnetic needle, of which the line T P is the natural direction or meridian, and let M be a magnet causing the needle S N to deviate from its meridian by some given angle, P C N, and holding

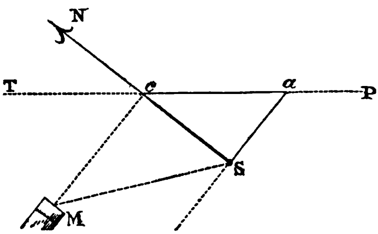
For the better convenience and accuracy of observation, the magnet (M, fig. 84,) may be placed on a moveable circular board and slide, as in fig. 82, so as to turn the poles into an opposite position, and adjust the distances without disturbing the bar.

137. This last magnetometer, as is evident, is convertible into the former by simply observing the deviation of the needle S N when the arm D T is at right angles to the magnetic meridian; and conversely the magnetometer, fig. 82, may be employed as a magnetometer of rectangular deflection, by turning the board E W, together with the needle and magnet, into such a position as will bring the needle again at right angles to the axial line of the board: if we then remove the magnet M, the needle returns to its meridian, and we are

---

it there by a force supposed to be collected in the pole M, and to operate in the direction M c, or at right angles to the actual position, S N, of the needle, and upon a centre of force, N or S, resident in the poles of the needle. Then, taking $a\,c$ to represent the force urging the needle in its natural meridian T P, and a S

Fig. 85.

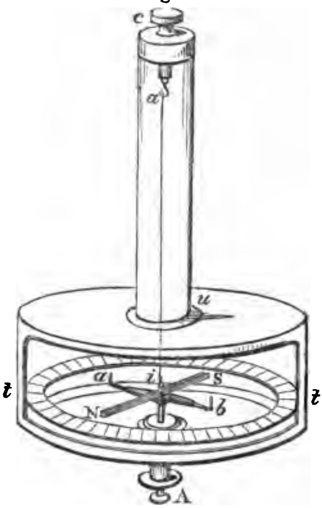


perpendicular to S N, the force by which the needle is sustained at a given angle $a\,c$ S, we have from the elements of trigonometry $c\,a : a\,\mathrm{S} :: $ sine of $a\,\mathrm{S}\,c$: sine of $a\,c\,\mathrm{S}$, and thus deduce $a\,\mathrm{S} = \frac{c\,a \times \sin.\,a\,c\,\mathrm{S}}{\sin.\,a\,\mathrm{S}\,c}$. But if, as in the case of the instrument (fig. 84), the distance M c be taken so great as to admit of the obliquity of the action in direction M S being neglected, and a S to be parallel to M c, or nearly so, and that this direction is always perpendicular to the needle, so that angle a S c becomes a constant,—being a right angle or unity,—and if, moreover, we only consider the comparative deflecting force without regard to the horizontal force $c\,a$ urging the needle to its natural meridian, then we may neglect sine of $a\,\mathrm{S}\,c$ and force $c\,a$, and we have for the above equation,—deflecting force $a\,\mathrm{S} = $ sine of $a\,c\,\mathrm{S}$.

enabled to observe the number of degrees by which it has been deflected. The great advantage of the latter arrangement, fig. 84, is that we are enabled to employ a very short needle, and yet observe the degree of deflection on a very large circular arc, *a o p*. This, however, might still be effected in fig. 82 by applying an index and large graduated arc to measure the angular movement of the extremity W of the board E W, about the centre *c*. In this case the angular quantity requisite to turn the axial line E W, in order to place the needle at right angles to that line, would represent accurately the deflection of the needle from its meridian.

138. *Magnetometer of Oscillation.*—This magnetical instrument consists of a light magnetic bar, or needle, N S, fig. 86, suspended by a fine silk filament *a i* from a fixed point *i*, within a graduated circular ring *a* S *b* N. The card and needle are mounted in a light wooden frame *t u t'*, carrying an elevated and narrow cap and nut *c* for the thread of suspension. The whole is placed on a slightly elevated table *t t'*, indicated in the figure, and so as to be moveable about a central pivot A, which, if prolonged, would pass through the centre of the needle and card

Fig. 86.



N *a* S *b*. The thread of suspension is attached to the extremity of a rod *c a*, which is acted on by a milled head and screw at *c*, so as to elevate or depress the bar S N by any small quantity; and adjusted to the plane of the graduated ring *a* S *b* N there is a forked lever *a b*, carried by a rod A *i*, passing through the

base of the frame, by which, in turning the milled head at A, the needle or bar may be seized, as it were, equally on each side the centre, and turned to any given points of the graduated circle.

The opposite points *t t'* of the card are marked zero, and the card is graduated up to 90 degrees on each side of these points. The axis of the bar S N is brought to coincide with these points by turning the frame carrying the card about the centre *o*. Two indexes N S of fine platinum wire are inserted in thin vertical slits cut on the extremities of the bar, and there are two sights in the frame at *t t'* by which the position of the opposite points of the card and needle may be accurately placed in the line of the magnetic meridian. The instrument being thus adjusted, the bar S N is turned aside by the forked lever *a b* to any given angular quantity shown on the card. The lever is then quickly turned back, and the bar allowed to vibrate for any given period. The times and arcs of vibration are carefully noted, and from this the force urging the bar is deduced.

The frame *t u t'* may be covered with a thin glass shade, to screen off currents of air from the vibrating needle, having an open end at *u* for the passage of the vertical narrow frame *c u*.

In the Edinburgh Philosophical Transactions, vol. xiii. Part I., and in the Transactions of the Royal Society for 1831, will be found a more detailed account of this instrument as applicable to the observation of the vibrations of a magnetic bar in an exhausted receiver.

139. The principle of this magnetometer is based on the fact that a vibrating magnetic needle may be considered as a species of pendulum; and the condition of the needle with regard to the magnetic directive force operating on it is very similar to that of a lever moveable on a horizontal axis, and acted on by any other force, such as gravity; such, for example, as the case of the compound pendulum; so that the same laws apply to both these cases. Now it is proved by the laws of oscillating bodies—

1°. That the time in which the same pendulum oscillates under different degrees of power will be inversely proportional to the square root of that power.

2°. That the force operating on the pendulum will be in the inverse ratio of the square of the time.

3°. That the time being the same, the force will be directly as the square of the number of vibrations.

Such are the general laws requisite to be kept in view for our present purpose. In the adaptation of the magnetic pendulum to the measurement of magnetic forces there are certain other considerations to be taken into the account, in the application of a vibrating bar or needle to particular and refined inquiries in magnetism, which will be noticed hereafter.

140. As a practical illustration of the application of the magnetometer of oscillation, fig. 86, to the measurement of magnetic forces, suppose the bar S N, under two different states of intensity, as produced by the methods of single and double touch, already described (94), had been found to make within given small arcs of vibration,

First 10 vibrations in 80 seconds (*a*);
Second 10 vibrations in 40 seconds (*b*);

then, by the laws just given (139), the force, or magnetic power of the bar, would in the second case (*b*) be four times as great as in the first (*a*).*

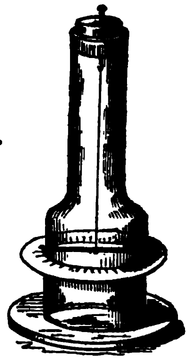
141. The rate of vibration of magnetic bars as a measure of force may be occasionally observed by a simple suspension from a fixed point. Coulombe deduced in this way the force

* Let the force urging the bar in the first case (*a*) be called f;
in the second case (*b*) „ f'.
We have then by law 1°, $80'' : 40'' :: \sqrt{f} : \sqrt{f'}$ or $\sqrt{f} : \sqrt{f'} :: 1 : 2$, that is, $\sqrt{f} = \frac{2\sqrt{f}}{1}$. If we call f unity or 1, then $\sqrt{f'} = 2$ and $f' = 4$; hence force f' is 4 times as great as force f. We have next by law 2°, $f : f' :: 40^2 : 80^2 :: 1^2 : 2^2$, or as 1 : 4, which is the same result. By law 3°, we have, in taking the number of vibrations performed in the same time, say for the first case (*a*), reduced to 40 seconds, $f : f' :: 5^2 : 10^2$, that is $:: 25 : 100$, or as 1 : 4, as in the other cases.

of the bars constituting his large compound magnet (107), as produced by various methods of magnetizing.

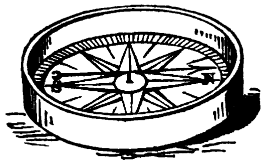
142. A very simple and ready form of the magnetometer of oscillation, especially in such investigations as require a short and fine vibrating needle, consists in the suspension of a small piece of magnetized steel wire within a common lamp-glass, closed at the top by a cork, through which the wire of suspension may be easily moved. A graduated ring of card-board should be made so as to encircle the glass at the position of the needle, and the whole may rest on a circular grooved piece of mahogany. This instrument is represented in fig. 87. The needle suspended within this glass may be put into a state of vibration by the external influence of a small piece of iron, or a weak magnet.

Fig. 87.



143. *The Compass.*—A magnetic needle or bar mounted on a fine centre, enclosed within a shallow box or metallic case, and furnished with a plane circular card, denoting the *chief* or *cardinal* points of the horizontal plane about us, constitutes a magnetical instrument termed the *compass*. This instrument, represented in figure 88, consists therefore of three principal parts: the needle S N, the card below it, and the case in which these are enclosed. The term *compass* is immediately derived from the card, which compasses, or involves, as it were, the whole plane of the horizon.

Fig. 88.



The compass needle, S N, is usually a light bar, set edgewise upon an agate centre, as already described (121): sometimes it consists of a thin piece of steel plate, tapering from the centre to the extremities, and may be of any dimensions, according to the size of the compass required. The Chinese employ very

small instruments, their needles not generally exceeding an inch in length. They consist of a short piece of fine cylindrical steel wire, and are suspended in the way already described (122), the centre of gravity being above the point of suspension.

The compass or card indicating the various points in the horizon, with reference to the direction of the magnetic needle, is either fixed in the case immediately under the needle S N, and separate from it, or is otherwise attached to the needle itself, as in figure 90, so as to traverse with it. In the former case it is constructed of card-board or metal; in the latter, it is made of some very light substance not subject to warp from heat or moisture, such as a thin plate of talc.

144. In the magnetic compass, the plane of the horizontal circle is divided into thirty-two parts by lines supposed to be drawn diametrically through the circle. These, as practically applied to the compass card, are called points of the compass, or in nautical language, rhumbs.* In marking the compass card, such as is represented in figure 89, the circle is first divided into two semicircles by a diameter S N, denoting the line of the magnetic meridian; and the north point, as being the most elementary or great point of reference, is usually distinguished by an ornamental arrow or fleur-de-lis. A diameter E W is next drawn at right angles to S N, by which we obtain the east and west line, and thus we have the four principal or elementary cardinal points. The quadrants of the circle between these four points are further and equally divided by two other diameters, producing four new rhumbs or points. These are named from their relative position in the compass.

The point midway between N and E, for example, being compounded as it were of the two directions, is termed north-

* From the Greek ρεμβω, to turn;—a vertical circle, in turning so as to intersect the horizontal plane in certain points, may be conceived to divide it into rhumbs.

east, and marked N E. That midway between N and W is in a similar way termed north-west, and marked N W. That

Fig. 89.

between S and W is termed south-west, and marked S W: between S and E is south-east, and marked S E.

We thus obtain eight principal points or rhumbs, and by continuing the division by diameters, bisecting the arcs contained by these first eight points, we obtain an additional eight points, making in all sixteen points: these additional points are named, as before, from their position in the compass.

The point midway between N and N E is termed north-north-east, as being nearer north than east, and is hence marked with two letters N, thus, N N E. In a similar way, the point between east and north-east is termed east-north-east, as being nearer the east, and is marked thus, E N E; and so on of the remaining bisected arcs: thus we have the points N N W and W N W for the points between north and west; S S W and W S W for the points between south and west; S S E and E S E for the points between south and east.

By further continuing the bisection of all the arcs included between these points, we again, as is evident, double the number of rhumbs, and obtain sixteen additional points, making in all thirty-two points: these, as in the previous instances, are named from their position in the compass, with the addition of the characteristic word *by*.

Thus the point midway between N and N N E is called north by east, and is marked N by E; that between N and N N W, north by west, and is marked N by W; the point between N E and N N E is called north-east by north, and is marked N E by N, and so on, leaning for the designation towards the nearest of the four elementary cardinal points. Thus the point midway between E and E N E is termed east by north, and is marked E by N. In this way we arrive at thirty-two rhumbs or divisions of the circle into points, which, taken in succession from the first or principal point, north, and carried round the circle in either direction, east or west,—suppose in the east direction,—will stand thus:

N.	E.	S.	W.
N. by E.	E. by S.	S. by W.	W. by N.
N N E.	E S E.	W S W.	W N W.
N E. by N.	S E. by S.	S W. by W.	N W. by W.
N E.	S E.	S W.	N W.
N E. by E.	S E. by S.	S W. by W.	N W. by N.
E N E.	S S E.	W S W.	N N W.
E. by N.	S. by E.	W. by S.	N. by W.

An enumeration of these successive points from memory is what sailors call 'Boxing the compass.'

145. More minute divisions of the compass card are estimated by what are called half and quarter points, each point being divided or supposed to be divided into four equal parts, so that any small angular quantity between either of the thirty-two divisions or points just enumerated, as for example between N. and N. by E., would be termed north a quarter east, or north half east, or three-quarters east, as the case may be: we then arrive at north by east, and so of all the other points.

Thus north by west, a little to the north or west, would be called north by west a quarter or half, &c. north, or a quarter or half, &c. west, as the case may be.

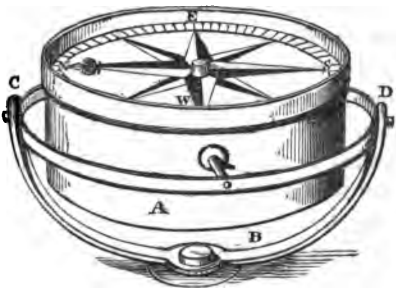
146. For more refined purposes, the compass is enclosed by a graduated circle divided into 360 degrees in the usual way, by which the rhumbs are estimated in angular quantities, each rhumb or point, as is evident, being the $\frac{1}{32}$nd part of 360°, or $\frac{360}{32} = 11° 15'$: a half point will be then 5° 37′ 30″; a quarter point 2° 48′ 45″.

147. When the compass card is fixed to the box or case in which it is enclosed, and the needle allowed to traverse over it, we have what is usually termed a *land compass:* it is commonly used by travellers for determining the different points of the horizon, the box being turned so as to bring the north and south points of the card immediately under the north and south poles of the needle (17). In this case all the other points, as referred to the magnetic meridian of the particular locality, are correctly placed. The land compass is also occasionally employed in the measurement of angles in surveying instruments. It may be, for general purposes, of any moderate size, from that of a common seal, up to a diameter of a foot. The land compass has usually a spring stop under the needle, by which it may be thrown up and retained clear of the point when not in use.

148. *The Sea Compass.*—Since a fixed compass card, as applied in the land compass, could not possibly be used on shipboard for determining the position of the cardinal points in reference to the magnetic meridian, because the vessel is continually varying its position, and is in continual motion, it becomes requisite to construct the compass card of some light substance not liable to warp or damage from heat and moisture, and attach it to the needle itself, so as to admit of both card and needle traversing together. If the needle be fixed to the card with the north and south poles immediately under the north and south points of the compass, then, as is evident, all

the points of the card will be correctly placed in reference to the magnetic meridian of the place, in whatever direction the vessel be turned; that is to say, supposing that no disturbing influence from iron or other causes exist in the ship itself.

Fig. 90.



This is, therefore, the principal distinction between the land and sea compass: the sea compass, or mariner's compass, is represented in the annexed fig. 90, in which S W N E is the magnetic needle with its card accurately poised on a fine central point within a bowl or case, A, of glass, metal, or wood; and in order to prevent any disturbance from the pitching and rolling of the ship, this bowl is set within a ring of metal, C A D, upon two axial pivots, which project from its opposite sides like the trunnions of a cannon: one of these is seen near A. The ring, in its turn, is set also upon axial pivots at C and D, in a line at right angles to the former, and which are either supported within a second semicircular or vertical ring, C B D, or on pivot notches in two brass plates fixed at C and D to the box or case in which the whole is usually enclosed, and which, on ship-board, has received the name of the *binnacle*. The centre of gravity of the mass is frequently kept far below these axial pivots of suspension by a ring, or small mass of lead, attached to the bottom of the compass bowl. The two brass circles, within which the compass bowl is thus supported, are called *gimbalds;* and it is clear that, by these, the card and needle will generally be preserved in a plane perpendicular to that of the point of suspension. In fact, any rolling motion transverse to the axis C D moves the ring C A D upon the axis C D; and any similar motion transverse

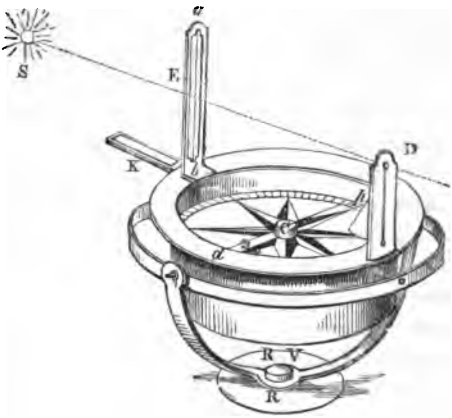
to the axis A moves the ring C A D upon the inner axis A,—the interior bowl, with the needle and card, being all the while maintained in a vertical position by the force of gravity. This form of the compass, although employed for the most part to guide the mariner across a trackless ocean, has still many other important practical applications, which will be noticed in their place.

149. *The Azimuth Compass.*—With a view to a complete apprehension of the nature and object of this kind of compass, we should understand that a great circle of the sphere, supposed to pass through the zenith or point immediately over our head, and cutting the horizon circle around us in any two points, is termed an *azimuth circle*, and the distance of the points in the horizon which they intersect, as measured from the true meridian of the place by an arc of the horizon, has been termed the *azimuth distance* of these points; such is, in fact, the direct meaning of the term *azimuth*, which is a pure Arabic word, signifying the distance between the meridian of a place and a vertical circle passing through the zenith, as referred to an arc of the horizon. This is termed the *true azimuth*. If we substitute the line of the magnetic meridian for the line of the true meridian, we have the *magnetic azimuth* of the points of intersection. If, therefore, we can determine the true and magnetic azimuths of any given points in the sphere about us, referred to an arc of the horizon, we may thence deduce the precise direction of the compass needle in respect of the true meridian of the place of observation. Now the true azimuth of any given point in the horizon is determinable by ordinary astronomical observation, and it is the object of the azimuth compass to find the magnetic azimuth.

150. The azimuth compass is represented in figure 91, and consists, in its latest and most improved form, of the sea compass just described, having two sight-vanes, D E, affixed to it, and in such way that the line of sight may pass immediately over the centre of the card C. The points of the compass depicted on the card are few, and for the most part

ornamental, but the circumference or outer ring of the card is very carefully divided into degrees and quarter parts, or 15′ of a degree. Immediately in the line of the sight-slit at D is a small triangular prism *p*, its lower face being formed into a lens, so as to give it a short focal distance. This prism is placed immediately over the divided circle of the compass card so that the eye at

Fig. 91.



D sees the divisions magnified and reflected in the prism; but since by the reflection the figures on the graduated circle become reversed, they are, to meet this condition, engraved on the card in a reverted position, so that the eye sees them in their true position. The opposite sight-vane E has a fine hair, *a b*, passing centrally and vertically through it, by which the line of sight, D E S, directed to any object, S, is caused to pass over the centre C of the card. The whole is mounted in gimbalds, as in the ordinary sea compass, the outer gimbald or ring being moveable on a central pivot R, so that the compass with its sights may be turned into any azimuth (149.) There is also a plane mirror K, moveable on a hinge at the back of the sight E, which may be placed at any angle required to reflect the image of any of the celestial bodies to the eye at D. There are also coloured glasses on hinges affixed to the sight-vane D, but not given in the figure, for screening off the light of the sun, or other object, when offensive to the eye.

151. *Application of the Azimuth Compass.*—This instru-

ment is applied in the following way: the prism p being carefully adjusted by small screws attached to it for that purpose, so as to obtain a distinct vision of the degrees of the divided card, the observer looks over the edge of the prism through the sight-line at D and through the vane E, at some celestial object, S, such as the sun or a star, when either in the horizon or above it, turning the instrument until the vertical hair $a\ b$, in the vane E, exactly bisects the object. At this instant he catches the reading of the card reflected to the eye by the prism p; in fact, he sees both at the same instant, taking care to note the degrees when the card is steady, at which moment he arrests it mechanically by a small spring-stop fixed in the instrument for that purpose, so as to read off the degrees corresponding to the line of sight D E S with greater precision. Now it is evident that the arc of the card intercepted between the magnetic meridian or line $p\ c\ d$ of the needle attached to it, and the line of sight D E S, is the magnetic azimuth distance of the object S, referred to the horizon (149); we may, in fact, conceive the horizontal circle to be only the limit of the plane of the compass card, and the object S to be brought down to the horizontal circle by a great circle of the sphere passing through the zenith and the object S, and intersecting the horizon in a given point; the distance of which, from the point of intersection of the magnetic meridian, is measured by the arc contained between them, and which is given in degrees of the compass card: this is what sailors call 'taking an azimuth or bearing by compass.' Having found the magnetic azimuth, we deduct it from the true azimuth of the body S, determinable by astronomical calculation, supposing the azimuth distance to be reckoned in each case both from the north, or both from the south; and the difference is the angular quantity by which the line of the magnetic needle differs from the true meridian of the place, and the declination will be either east or west, according as the true azimuth falls on the right or left of the magnetic. The best time for an observation is when the object is in or near

the horizon. If the sun be observed, the observation should be taken when the lower limb is just above the horizon, for the centre is then nearly in the horizon, but is seen above it on account of the refraction of the atmosphere.

We are indebted to Gilbert for the more correct and complete method of the prism, which may be considered as a great boon to nautical science.

The common azimuth compass is merely furnished with two common sights attached to it. Mr. M[c]Culloch greatly improved this form of the instrument by perfecting the application of the sights, and using a lens and vernier to read off the divisions of the card.

When, instead of measuring the distance of a celestial object as referred to the horizon from the true or the magnetic north and south points, we measure it from the true or the magnetic east and west points of the horizon, then that distance is termed the *true* or the *magnetic amplitude* of the object, as the case may be. As this measurement is frequently resorted to, the azimuth compass has been also occasionally termed an *amplitude compass*. Either method, as is evident, may be employed for determining the difference in the direction of the magnetic and true meridians of any given place, the real amplitude being found, as before, by astronomical calculation, the magnetic amplitude by the compass.

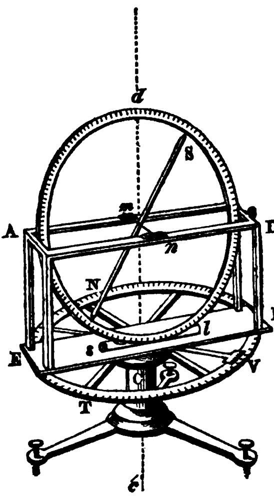
152. In the various applications of the compass, both on shore and at sea, it is of great importance to maintain the needle in as perfect a state of quietude as possible, and that without damaging the sensibility of the instrument. In the compass as improved by the author of this work, so long since as the year 1832, the needle is surrounded by a dense ring of copper, which, together with some other recent arrangements in the preparation and mounting of the needle and card, is so effective, that the usual inconvenient oscillations, especially at sea, are altogether avoided. This instrument will be more particularly described in our chapter on the *mariner's compass*.

153. *The Dipping Needle.*—We have already seen (21)

that the natural position of the magnetic needle, when free to move into any position, is not always horizontal, but is a combination of a horizontal and vertical direction, so that the needle commonly endeavours to place itself in the plane of the magnetic meridian, in a direction more or less inclined to the horizon. The magnetical instrument by which the amount of this inclination is determined has been termed the *dipping needle*, and is represented in fig. 92.

N S represents a light magnetic bar or needle of a long lozenge form, about 10 inches in length, which, previously to being rendered magnetic, is set on a short axis *m n*, and is very accurately poised about its centre of gravity, through which the axis is passed, so as to be quite indifferent as to position (21). The axis *m n* is turned down at its extremities to very fine cylindrical pivots; these rest on two finely polished agate planes *m n*, supported on two cross bars A D of a light rectangular frame A D B E. The platform or cross-piece, E B, of this frame is solid, and fixed to a circular plate beneath, accurately ground to a similar plate fixed on a vertical pillar C, so that by means of a vertical axis which plays in a socket in the pillar C, the whole may be turned evenly and centrally round into any azimuth (149). The cross-piece E B, which has a level s *l* fixed in it, gives support to a finely divided circle A *d l*, in the plane of which the bar N S moves: the axis *m n* is so placed as to pass accurately through the centre of this circle. The whole is mounted on the central pillar C, and can, as just

Fig. 92.



observed, be turned into any required azimuth about a supposed vertical axis *c d*, passing through the centre of the needle. The precise angular quantity through which the needle is turned is measured by a contrivance called a *vernier*, V, attached to the under part of the platform E B, and a graduated azimuth circle T N V, fixed to the central pillar of support; the whole is placed on a light firm base, furnished with three levelling screws, for the requisite levelling of the instrument. The vertical circle A *d l* is divided upon silver to 10′ of a degree. The agate pieces *m n* are adjustable to the same horizontal plane by screws bearing upon their lower edges, and there is a light interior frame acted on by a lever at D, furnished with y-pieces at *m n*, and moveable on an axis at one extremity, A, by which the axis of the needle S N may be lifted off the agate planes *m n*, and be again let down on them without disturbing its final position. The whole is covered by a light case of wood and glass resting on the platform-piece E B, but not represented in the figure, so as to shield the needle from the air; and there are also two moveable arms attached to a horizontal bar connected with the case, which carry lenses for reading off the degrees of the divided circle, S.

The instrument here described is after the construction of M. Gambey, of Paris, who is celebrated for the accuracy and beauty of such instruments. There are other forms of construction of the dipping needle adopted in this country, also worthy of attention, but they involve precisely the same principles. The dipping needle of Messrs. W. and T. Gilbert is amongst these, and is a very perfect instrument. In every kind of dipping needle, however, upon these principles, the mechanical difficulty of a perfect construction is immense, since for absolute perfection we require to adjust the centre of gravity of the needle within the one-millionth of an inch of the truth: how great, therefore, must be the disturbance produced by inequalities in the bearing points of the axis or other very small errors of construction!

154. In order to determine by this instrument the dip or inclination of the magnetic needle in any given spot, we place the instrument on a steady base, free from the presence of iron, and having accurately levelled it, proceed to adjust the graduated circle A *d l* in the magnetic meridian. This is effected either by removing the needle of inclination S N, and placing a balanced horizontal needle, made expressly for the purpose, within the frame A *m* D *n*, or in any other situation adapted to it, or by turning the instrument so as to bring the needle into a vertical position. It will be then at right angles to the magnetic meridian; and we have then only to turn it 90 degrees from this point, as shown on the azimuth circle T N V. Having determined the direction of the magnetic meridian, the plane of the circle A *d l* is finally secured in that direction by a small clamp-screw at C. We now remove the horizontal needle, if that be employed, and replace the needle of inclination S N, allowing it to vibrate freely. When it is at rest, we turn the milled head lever at D, and lift the axis *m n* gently off the agate planes by means of the y-pieces; when again let down it will be accurately in the centre, and in the plane of the divided circle. Supposing we had an absolutely perfect instrument, the needle would now mark the precise angle of inclination at the place of observation; but there are mechanical errors, as just observed, quite inseparable from the construction of the instrument, which we can only hope to compensate by a mean of experiments. We therefore first take a few successive observations, and note the angle at which the needle rests after putting it into vibration. This should be repeated with the axis *m n* reversed in position on the agates. We then turn the face of the instrument 180°, as shown by the circle T N V, that is, completely round, and make a similar number of observations. We now remove the needle S N, and by the processes of magnetizing before given (92) (99), to reverse its poles, and take a similar series of observations; so that we have then to take the mean of a given number of observations,—say 10.

First, with the face of the instrument, suppose			to the East.
Second,	„	„	to the West.
Thirdly, with inverted poles,			face to the East.
Fourthly,	„	„	to the West.

The nearer these observations accord, the more perfect is the instrument; but they will certainly differ by some small quantity. If we add the whole together, however, and divide by the number of observations, the resulting quotient will be very near the true inclination of the needle. Thus, the inclination of the magnetic needle in the gardens of the Athenæum at Plymouth was found to be, in November, 1831, by Gambey's instrument, 69° 27′ 6″. The observations were taken by Captain Fitzroy, R.N., and the author, previously to the sailing of the *Beagle* on her second voyage. A similar result was obtained by means of Gilbert's dipping needle.

155. It being almost impossible to construct an absolutely perfect instrument for determining the inclination of the magnetic needle at once and by a direct experiment, other indirect methods have been proposed, by which the errors inseparable from the difficulty of construction are sought to be avoided. One of these consists in observing the angular deviation of the needle from the vertical position taken in a series of planes at right angles to each other, by turning the instrument round on its vertical axis. If we take the squares of the tangents of the observed angles of deflection from the vertical in each pair of planes, and deduce a mean from these results, we obtain the square of the tangent of an angle, which, if added to the true angle of inclination, would complete a right angle or 90°, hence called the *complement of the dip*: from this it is evident that the true angle of inclination can readily be found by the ordinary Mathematical Tables.*

* In the annexed fig. 93, let C be the centre or axis of the needle, C P the true position of inclination from the horizontal line C H in the plane of the magnetic meridian *m* M. Then in turning round the instrument, it is found that when the face is at C *m*, or at right angles to the meridian, *m* M, the needle will be in a vertical position, C *m*, and will, in

156. Another method of observation consists in observing the time of a given number of vibrations of the needle in the plane of the meridian, and in a plane east and west, or at right angles to this; that is to say, in the inclined and vertical positions of the needle. We then divide the square of the times, say of 100 vibrations in the plane of the meridian, by the square of the time of the same number when the needle is vertical in an east and west plane; the quotient is the sine of the true angle of inclination, from which the angle itself is easily found.

This method principally applies to places in which the dip is not very considerable. When the inclination is considerable the following method has been resorted to: first observe the time of a given number of vibrations in the plane of the meridian, as before; then suspend the needle by a silk fibre, branching and extending below a little on each side the centre, so as to produce a perfectly horizontal position. Let the needle now vibrate freely in a horizontal plane. Divide the square of the time of a given number of vibrations in the inclined posi-

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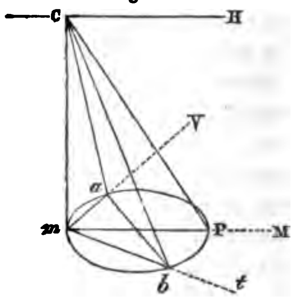
turning, take all intermediate positions, describing a cone, m C P b m a. Let m C a and m C b be the angles of deviation from C M, as observed in two planes, m V, m t, at right angles to each other. Then in right-angled triangle, $a\,m\,b$, we have, Euclid 47, Book I. $(m\,a)^2 + (m\,b)^2 = (a\,b)^2 = (m\,\text{P})^2$, since $a\,b$ and m P are diameters of the same circle, $m\,a$ P b; but by the elements of trigonometry, $m\,a$ and $m\,b$ are the tangents of the observed angles, m C a and $m\,a\,b$: we may hence obtain from the squares of these tangents the square of m P, which is in like manner the tangent of the angle m C P; that is to say, of the complement of the angle P C H, or true inclination below the horizontal line C H. From this the angle of inclination, P C H, or true dip, may, as is evident, be deduced by the ordinary Trigonometrical Tables.

Fig. 93.



tion by the square of the time of the same number in the horizontal position, and we then have the cosine of the true inclination or dip, from which the angle itself is easily found by the ordinary Tables.*

As it is of importance in this experiment to obtain a true horizontal direction, we cannot be too careful in completing the position of suspension. The following is a simple and ready method of observing whether the needle be suspended horizontally. Fill an open vessel of any kind with water, which should be tinted with a little common blue; hold the needle by the suspension thread over the water, so as to observe the reflected image of the needle: if the two lines of the needle and its image be parallel, then it is evident, from the nature of the experiment, that the needle is perfectly horizontal; if not, we must adjust the branch of suspension until this result be obtained.†

* These processes are founded on the resolution of the force causing the needle to vibrate. When oscillating in its natural or inclined position, it oscillates by the action of the whole *directive power;* but when oscillating in a vertical or horizontal position, only a portion of the whole directive power comes into play. Completing the trigonometrical construction of the forces according to the method given, fig. 83, p. 122, the force in the vertical position becomes finally represented by the sine of the angle of inclination, and in the horizontal position by the cosine—calling the whole, or total force, unity or 1. Let, therefore, d express the dip or angle of inclination, t and T the times of a given number of oscillations in the inclined and vertical positions of the dipping needle; then, as the forces are inversely proportional to the squares of the times of vibration (139), we have—

$$1 : \sin. d :: T^2 : t^2;$$

that is to say,

$$\sin. d = \frac{t^2}{T^2}.$$

Taking the oscillations in the inclined and horizontal positions, we have, in substituting cos. d for sin. d,

$$\cos. d = \frac{t^2}{T^2}.$$

† This method of obtaining a horizontal line was first proposed by the author in 1832, and will be found in his paper on the Horizontal Needle,

157. *Mayer's Dipping Needle.*—With a view of avoiding the errors incidental to the dipping needle as usually constructed, Mayer employed a needle having a projecting steel screw, very accurately centered, on which a small brass ball was made to traverse, so as to deflect the needle from the true inclination by any given quantity. In this case, as is evident, we never get the correct dip in any one observation, the position of the needle being partly due to gravity: by reversing the instrument, however, as in the preceding experiments (154), the effect of gravity becomes separated from the magnetic force, and thus the true dip is ascertained.

158. All these indirect methods of observation, although extremely worthy of consideration, are still open to many sources of error inseparable from such investigations, and it is very doubtful after all, whether, by a well-constructed instrument such as we have described, fig. 92, we may not, by a series of reversed observations (154), obtain as near an approximation to the truth as is likely to be arrived at.

Sabine, in 1821, determined the inclination of the needle in London, by the two methods of oscillation, and by Mayer's needle, and arrived at the three following results:

Mayer's needle, 70° 2′·9. Methods of oscillation, 70° 4′ and 70° 2′·6.

Barlow, a few years subsequently, by Gilbert's dipping needle, obtained the following:

69° 58′·4. 70° 0′. 69° 53′. 70° 1′·8.

By the latter observations with Gilbert's needle, there appears to be an uncertainty or difference in the action of the needle, of about 9′, which, considering the nature of the force acting on it, is inconsiderable. If we suppose the needle

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in the 13th vol. of the Edinb. Phil. Transactions, Part I. Plate II. It is extremely simple and perfect, and has been since practised in the Magnetic Observatory at Greenwich, and in other observatories. The error of horizontality by reflection being double the real error, it is very easy to detect the least deviation from the horizontal position.

within 9′ of its true position, then the force acting on it, being as the sine of the inclination, will be to the force acting on it at 90°, or at right angles from its true position, as radius to the sine of 9′, or as 1 : 0026. Now this is so small a result, that the least defect in the balancing, or in the axis of motion, or any minute roughness in the agate planes, or the interposition of dust, or other accidental causes of disturbance, would be sufficient to arrest the needle in such a position.

159. The axis of the dipping needle by Michell, made by Nairne, for the Board of Longitude, in 1772, rested on friction-wheels, four inches in diameter; the extremities of the axis being of gold, alloyed with copper, and turned down to fine pivots. The needle in this instrument was a foot in length. The principle of agate planes was adopted by Cavendish, in the dipping needle made for the Royal Society, in 1776.

The most refined method of mounting the dipping needle is unquestionably the method of friction-wheels. Two main wheels only should be employed for the extremities of the axis to roll on; these should be about two inches in diameter, mounted on fine pivots, set in jewels, and with a flat polished circumference. To prevent the axis of the dipping needle from slipping to either side, similar but smaller check-wheels should be employed, as represented in fig. 75, page 111: this is, incomparably, the best method of obtaining great freedom of motion.

160. *Dipping Needle Deflector.*—We must not close this branch of our subject without noticing a most valuable and ingenious instrument, by Mr. R. W. Fox, of Falmouth, and termed by him a *dipping needle deflector*. In this instrument the needle, being accurately poised, is mounted on an axis, and placed within a cylindrical case, faced with glass, similar to a watch case. The needle is about seven inches in length, and the pivots of the axis turn in jewels; and there is a finely divided circle, with a vernier, for estimating the inclination of the needle. The whole is set vertically on a firm tripod base,

with levelling screws, and admits of being turned into any azimuth. A small telescope, moveable in a vertical plane, and furnished with cross wires, is attached to the back of the case, to which is added a brass tube with a lens, for throwing a bright spot of light upon a white plate behind it. For solar observations there are also two small tubes of brass, which may be applied to the telescope tube, for receiving two cylindrical magnets, and which are so arranged as to admit of being turned into certain positions for deflecting the needle. The back of the case has also a divided circle on it, with a vernier carried by an arm at right angles to the telescope.

In measuring the angle of the dip by this instrument, we carry out a series of common observations, in the way already described (154). The observed dip is to be corrected by screwing on one of the deflectors at right angles to the telescope tube, so as to deflect that end of the needle nearest to it. The deflector is now turned a given number of degrees from the observed dip, so as to deflect the needle by a certain amount, and then a similar number of degrees in the reverse way, so as to deflect the needle in the opposite direction; then, supposing the needle, in these two cases, to stand first at 52°, and secondly, at 87° 10′, the mean of these would be 69° 35′, the angular quantity sought.

Our limits do not admit of a more detailed notice of this beautiful instrument, which is not only a dipping needle, but is also available for a great variety of important magnetic researches, and has been successfully and extensively employed. A particular account of it, however, will be found in the Reports of the Royal Polytechnic Society of Cornwall.

161. The following are the most celebrated of the instruments hitherto employed for determining the dip of the magnetic needle:—Michell's dipping needle, described in the Philosophical Transactions, in 1772; Cavendish, in 1776; dipping needle by Dr. Lorimer, to be used at sea, in 1775; dipping needle by Daniel Bernouilli; dipping needle by Mayer, of Gottingen, in 1814; dipping needle by Messrs. W. and T.

Gilbert; dipping needle by Gambey, of Paris, 1830; Professor Lloyd's instrument for observing the dip (Memoirs of Royal Irish Academy, 1835); Fox's dipping needle deflector.

INSTRUMENTS FOR DETERMINING THE DECLINATION, AND FOR MEASURING CERTAIN SMALL PERIODICAL CHANGES IN THE HORIZONTAL AND INCLINED NEEDLES.

162. The declination and inclination of the magnetic needle not being, as just observed, everywhere the same, and being, further, found liable to certain small fluctuations of a secular character, it becomes a matter of great scientific importance to ascertain the amount and nature of such changes; and with this view certain instruments have been invented, which remain now to be briefly described.

The mere fact of the declination of the horizontal needle, together with an approximative value of the angular difference with the true meridian, may be arrived at by two very simple methods. If the observation be made on shore, it will be sufficient to draw a line, in the direction of the true meridian, upon some firm plane base, such as a block of marble or wood. The direction of this line may be ascertained by means of a linear shadow, thrown, when the sun is in the meridian, from a plumb-line, or a slender needle set upright on the plane, and which may be sufficiently well determined by watching the shadow, and taking it at the least length; or by any other simple astronomical observation. Having determined, and carefully laid down, this line of the true meridian, we place a delicate compass, with a graduated card (143), immediately on it, bringing the north or south points of the card coincident with the true meridian line. If the card be well graduated, the needle will show, to a fraction of a degree, its deviation either east or west of the meridian. If a fine compass be not at hand, we may employ a simple magnetic needle, centered on the line of the meridian, and shielded from the air. Having marked its line of direction, proceed to mea-

sure the angle of this direction with the meridian by a common protractor or other mathematical instrument. The magnetometer of oscillation, accurately centered on the true meridian, may be advantageously employed in this observation.

A second similar method, and which, with a little care, is available at sea, consists in suspending a plumb-line, when the sun is in the meridian, over the common sea compass, and in such way as to cause the shadow to fall directly across its centre; then the rhumb, or point, on which the shadow falls, is the declination or variation of the needle. If the compass card have a divided circle about it, the observation is, of course, more exact; but we may always determine it within a quarter point. The exact moment at which the observation should be made, is when the shadow is the shortest, or when a good time-keeper is at the hour of the meridian.

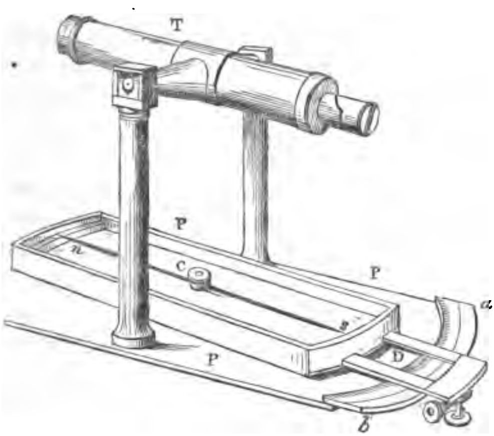
Such methods, although very practicable and simple, for common purposes, are still not sufficiently refined, when we require to observe the declination of the magnetic needle, so as to involve angular quantities of small amount. In this case we must have recourse to magnetical instruments, constructed for this particular purpose,—such as the azimuth compass, already described. For the purpose of detecting and registering extremely small secular changes in the direction of the needle, we require magnetical instruments of the most delicate and refined description; these are principally the following:

163. *The Variation Compass.*—The most perfect of this class of instrument is that employed by the late Colonel Beaufoy, for the capital series of observations recorded by him in the 'Annals of Philosophy,' between the years 1813 and 1821. It is partially represented in fig. 94.

In this compass, the needle *s n* is a slender and pointed cylinder, 10 inches long, and only the $\frac{1}{500}$th of an inch in diameter. This needle is placed within a narrow cylindrical case or box *s* c *n*, the base of which is a brass plate moveable upon a central pin c, under the point of suspension of the needle.

This plate has two segments of a circle, one under the needle at each extremity, upon which is drawn a central or axial line, and at the extremity D of the box is a vernier and index, pointing to the divisions of a finely divided arc *a b*, attached to a large plate of brass, P P, beneath it, and moveable also on the central pin at C. The plate C D, carrying the vernier, has

Fig. 94.



a frame furnished with a clamp screw and a tangent screw, one to fix it to the arc *a b*, the other to give it a slow motion about the centre C. The lower plate P P sustains a transit telescope T immediately over the centre of the needle. The whole is placed on a firm mahogany base not shown in the figure; this rests on three levelling screws, and there is also a microscope placed over one extremity, *s*, of the needle, by which its coincidence with the axial line on the segment beneath is minutely observed. It being our object to convey a simple idea of the principle of this instrument, several minor details have been omitted, both in the figure and the description, for the sake of perspicuity.

In order to observe from time to time the smallest variation in the direction of the needle with this instrument, it is first

accurately levelled, and the vernier D set at zero of the arc. The telescope T, with an additional object-glass, is then directed to the axial marks under the extremities *s n* of the needle, by which we ascertain them to be in the plane of the motion of the telescope; if not, the telescope can be rectified so that they shall be. We now adjust the telescope in the true meridian by the usual transit of the stars across it; an adjusting screw acting on the brass plate P P, carrying the telescope and fixed to the base beneath, but not shown in the figure, being used to turn the whole about the centre C when requisite. If the instrument is to be a fixture, distant marks are set up to fix the direction of that line. We now allow the needle to settle quietly, and then turn the box *s* C *n* until the needle corresponds with the axial line or the segments beneath; the clamp screw, in the frame at D, is then fixed, and we proceed to give the compass box a slow motion by means of the side or tangent screw, until an exact coincidence, as seen through the microscope, is obtained: the vernier at D now shows the precise variation of the line of the needle from the true meridian.*

164. *Barlow's Variation Needle.*—The small amount of variation in the direction of the magnetic needle observable by such instruments as the variation compass may be considerably magnified by a most ingenious process proposed in the year 1823, by Professor Barlow, of Woolwich. It occurred to this distinguished philosopher, that if a delicately suspended needle were placed under the influence of magnetic bars, so as to deflect it from the meridian, even so as to render it indifferent as to directive position, then the changes in the directive force operating on it, whatever it be, would become extremely sensible, and distinctly marked by changes in the position of the needle. Suppose, for example, by the application of a magnetic bar, as represented in figs. 82, 84, the needle were deflected so as to stand 8 points from its natural direction, it

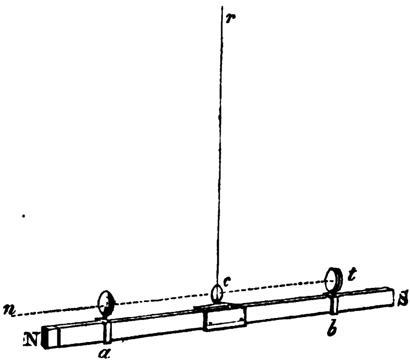
* For a particular description of this instrument, see 'Annals of Philosophy,' August, 1813.

would then be observed to vary through more than 3 degrees in the course of 24 hours.

In this kind of experiment the needle of observation may be brought, by means of magnets properly disposed, into any required position. We may, for example, deflect it eastward or westward of its meridian, or even reverse its position altogether. We shall have occasion to refer to the results of this method of observation hereafter.

165. *The Declination Magnet.*—This instrument consists of a delicately suspended magnetic bar N S, fig. 95, about 2 feet in length, 1½ inch wide, and ¼ of an inch thick. This bar is furnished with two sliders of brass, *a b*, one of which, *a*, carries a lens, the other, *b*, a compound plane glass, consisting of two plane glasses brought close together, and having between them a cross of cobwebs adjusted to the focus of the lens. The suspension thread consists of several fibres of unspun silk, and deprived of all torsion. The bar is rendered perfectly horizontal, and the whole is enclosed in an appropriate circular case to shield it from the air.

Fig. 95.



The declination of the magnet is observed with this instrument by means of a theodolite and telescope placed firmly at the distance of 8 feet, and directed in the axis of the bar, in the line of sight *n t*, through the lens *a*, to the cross of cobwebs in the plane glass *b*, and which moves as the magnet moves. We are thus enabled to record the apparent position of the magnet at any instant with respect to the reading of the divided limb

of the theodolite. Now the telescope of the theodolite can be turned so as to observe the stars as they pass over the true meridian, so that the difference in the reading of the theodolite, when directed to the true meridian, and when directed to the cross of cobwebs in the magnet, is the declination of the magnet, or angles of inclination of the magnetic and true meridians, at any particular time.

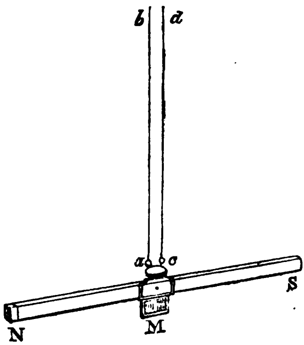
We are indebted to Professor Gauss, of Gottingen, for this method of observation, by which the most minute motions of a suspended bar are rendered sensible. In fact, a magnetic bar, thus suspended and observed, is seldom seen perfectly at rest, and is, moreover, found subject to certain periodical disturbances; it becomes, therefore, requisite to watch the magnified motions, and determine from these the mean position of the bar, as the cross passes through the field of view of the telescope. To get the mean position accurately, we require at least three readings of the magnetic oscillation; the interval between the first and last reading being equal to the time of a double oscillation.

The declination magnet employed by Professor Lloyd in the Magnetic Observatory at Trinity College, Dublin, is only 15 inches in length; the glass *b*, fig. 95, carries a divided scale, the true meridian is determined by a regular transit telescope, and the theodolite of observation is placed in the meridian of the transit, in a point of the plane cut by the magnetic axis of the suspended bar.

166. *The Horizontal Force Magnet.*—The object of this magnetical instrument is to measure and determine certain small changes found to occur from time to time on the directive force of the horizontal needle. It consists of a magnetic bar, N S, fig. 96, similar to the former, suspended by two parallel threads of unspun silk fibres, *a b* and *c d*; a mirror, M, is attached to the centre of the bar, in which is reflected a divided scale fixed to a wall about 8 feet distant from it. The method of observation with this instrument is as follows. The suspended bar is first constrained to take an east and

west direction, or a direction at right angles to the magnetic meridian, or nearly so. This is effected by twisting the bifilar suspension in the way already described (133). The bar is consequently placed in equilibrio by the reactive force of the suspension with the force tending to restore it to its original position at any given instant, so that the least change in that force, whatever it be, is accompanied by a slight movement of the actual direction of the bar. Now this movement, however small, is discernible by means of a reading telescope directed towards the mirror, in which the fixed scale is reflected, different numbers of the scale being seen in the telescope, and the divisions estimated to the last degree of precision. By this instrument it is found that the magnet is drawn less towards the north at noon, and more towards evening.

Fig. 96.



In the bifilar suspension, as applied to this instrument, the torsion-circle, by which the threads are turned upon each other (133), is placed at *a c*, fig. 96, on the brass frame or stirrup carrying the bar and mirror, and the threads of suspension pass round grooved wheels, so as to admit of the distance between them being adjusted and varied if required.

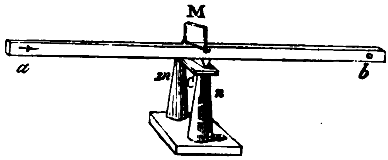
The horizontal force magnet, as employed by Professor Lloyd at Dublin, carries a light tube beneath the stirrup, in which is a lens and finely divided scale, for directing the line of sight, as in the former instrument (165), forming what is termed a *collimator*.

167. With a view of restraining the oscillations of the horizontal and bifilar magnetometers, the magnets are now placed within the influence of thick bars of copper, by which they are surrounded, after the method first proposed and

applied by the author to the purpose of arresting the oscillations of the compass as used at sea, and rendering the needle steady under the motion of the ship (152).

168. *The Vertical Force Magnet.*—This instrument is applicable to small changes in the force by which the horizontal needle tends to take up a position more or less inclined to the horizon. A magnetic bar, *a b*, fig. 97, is mounted on a central axis at C, reduced to knife edge, similar to the axis of a common balance: this axis rests on plates of agate, based on the pillars *m n* of a solid frame of brass. There are two screw-pieces, *a b*, one at each end of the bar, by which any degree of inclination in a position of rest can be changed, or the centre of gravity of the whole raised or depressed. A mirror, M, is fixed centrally over the axis, in which is reflected a finely divided scale fixed to the stand of a telescope, directed towards the mirror, as with the preceding instruments.

Fig. 97.



The instrument being properly adjusted in the magnetic meridian, the observer sees, through a glass plate in the side of the box in which the magnet is enclosed, the divisions of the vertical scale fixed to the stand of the reading telescope, as reflected in the mirror: as the magnet inclines more or less to the horizon, these divisions and numbers on the scale are observed to change, and thus the most minute variation of the force, which causes the magnet to incline, is finally deduced. It is, for example, found by this instrument, that at 2 A. M. the north pole is less drawn towards the horizon than at 4 P. M.

169. The magnetical instruments last described, viz. the *Declination Magnet*, the *Horizontal Force Magnet*, and the *Vertical Force Magnet*, have been set up, in various parts of the world, in magnetic observatories peculiarly fitted for their reception; as, for example, at Greenwich, in Canada, St.

Helena, the Cape of Good Hope, and Van Dieman's Island. These have been established at the cost of the British Government. The Greenwich magnetic observatory is under the direction of the Astronomer Royal; those in Canada, St. Helena, and the Cape, have been placed under the Ordnance department; and a staff of observers for them has been selected from among the officers and non-commissioned officers of the Royal Artillery. The observatory at Van Dieman's Island was intrusted to the care of officers of the Royal Navy. Other observatories have been established in other places; as, for example, at Dublin, conducted at the expense of the University of Trinity College, under the superintendence of Professor Lloyd; the Makerstown observatory at Kelso, in Scotland, supported at the private cost of General Sir Thomas Makdougall Brisbane, Bart.; the magnetic observatories at Madras, Singapore, Simla, and Trevandrum, at the expense of the East India Company; at St. Petersburg, Catherinenbourg, Barnaoul, Nertchinsk, Sitka and Tiflis, supported by the Russian Government, which has also furnished the Russian Mission at Pekin with magnetical instruments. There are, also, observatories at Paris, Gottingen, Milan, Munich, Prague, &c.; and it is proposed, when a sufficient number of observations shall have been made (a work of considerable magnitude and labour), to construct charts, showing the values of the *declination*, *inclination*, and *intensity* of the magnetic elements over the surface of the globe.

170. In the construction of these observatories, the presence of iron is entirely excluded, and the most elaborate care has been taken to perfect the observations. The position of the three instruments is such as not to influence each other's motions, and it admits of the observer directing his reading telescope to either instrument without changing his position. This is combined with a ready means of observing, by the ordinary astronomical methods, transits of the stars, and of determining the relative positions of the lines of the true and magnetic meridians at any given moment: there is also a com-

plete set of corrections for changes likely to be effected in the bars from heat. Index errors and other disturbing causes have also been deduced, and thus nothing is left unprovided for requisite to an accurate result.

Observations with these instruments have been generally made every two hours, and the divisions of the respective scales, as reflected in the mirror of each instrument, duly noted: these readings are subsequently converted into measures of the changes in the declination or variation to minutes or seconds of a degree, and of the horizontal and vertical forces to thousandth parts of the whole or total force operating on the bars.

171. These two-hourly observations have been lately superseded in the observatory at Greenwich by a sort of perpetual registration of the instruments, by means of photography, and with so much success, as to entitle Mr. Ronalds and Mr. Brooke, the inventors of the process, to a reward of £500, offered by the Government for the best means of saving a large and severe amount of personal labour. A general idea may be formed of this process by imagining that instead of the scale of inches being reflected from the mirrors, a narrow ray of light from a lamp is reflected, and which moves as the mirror moves, and that in this way a spot of light is made to travel upon a screen fixed so as to receive it, and over which it moves without the least friction;—conceive now that this spot of light moves upon a screen of photographic or sensitive paper, enclosed within a dark and enclosed space; and imagine the sensitive paper to be rolled round a cylinder, turning upon an horizontal axis once in twenty-four hours, then the path of the light thrown from the mirror upon the paper will be recorded from moment to moment by the discoloration of the paper in consecutive points. Finally, the impression is made permanent at the end of each twenty-four hours by removing the paper and applying the usual photographic means for that purpose. The papers thus preserved become perpetual records of the continued variation of the forces operating on the bars.

In the Greenwich observatory, the registrations of the light from the mirror of the horizontal force magnet (166) correspond to a circle of twenty-four feet radius, and extend over five inches of the photographic scale, so that a variation of the one-thousandth part of the horizontal force acting on the magnet will cause a deviation of the spot of light through $\frac{24}{100}$ of an inch on the paper; and in the vertical force, $\frac{52}{100}$ of an inch are estimated in a similar way.

The magnets, lamps, and registering cylinders are shut up in long rectangular cases of zinc, and the ordinary meteorological instruments are also registered in conjunction with the magnets.

We are indebted to Gauss, a celebrated German astronomer and mathematician, for the first commencement of regular magnetic observatories fitted with instruments of this kind; and although our own country cannot claim any merit in originating such observatories, she has nevertheless speedily followed out the system with a generous, noble, and liberal ardour, both at home and in her colonies, in every way worthy of the national science.

172. We have now gone carefully through the principal theoretical and practical phenomena requisite to the progress of further investigation in this most interesting branch of natural knowledge, and without a full comprehension of which the many wonderful and important relations of magnetism to the system of the world, and to the general purposes of mankind, cannot be either fully appreciated or understood. It will be our endeavour in a succeeding Part to apply the knowledge we have thus acquired to the elucidation of the several physical inquiries which the mysterious, subtle and universal agency of magnetism involves.

END OF PARTS I. AND II.

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RUDIMENTARY

MAGNETISM:

BEING

A CONCISE EXPOSITION OF

THE

GENERAL PRINCIPLES OF MAGNETICAL SCIENCE

AND

THE PURPOSES TO WHICH IT HAS BEEN APPLIED.

With Fifty-six Illustrations.

PART III.

BY

SIR W. SNOW HARRIS, F.R.S., &c.

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PREFACE.

It has been the author's endeavour to carry out in this supplementary or second volume of Rudimentary Magnetism the design specified in the Preface to Parts I. and II.; that is to say, an extension of elementary principles to an important class of natural magnetic phenomena, intimately connected with the physical universe, and with the prosperity and advancement of civilized life. Keeping in view the professed rudimentary character of the series of publications of which these volumes constitute a part, the author has thought that no kind of auxiliary information calculated to assist the student to a clear comprehension of the matter immediately before him should be considered as out of place in this work, however elementary and simple its character; so that the necessity of consulting other works, which may not always be at hand, may be as far as possible avoided. This, it is presumed, will be admitted as a sufficient ground for having in some instances referred to explanatory notes, which by the more advanced reader may be considered superfluous.

W. Snow Harris.

Plymouth, February, 1852.

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Page 119, line 7 from the top, *for* "sign of the angle," *read* "angle."
" 133, " 4, under E. *for* S.E. by S. *read* S.E. by E.
" " " 3, under S. *for* W.S.W. *read* S.S.W.
" " " 4, under S. *for* S.W. by W. *read* S.W. by S.

RUDIMENTARY MAGNETISM.

VI.

LAWS OF MAGNETIC FORCE.

Preliminary Observations—Experiments of Hawksbee, Brook Taylor, and Whiston; Muschenbroek's Experiments—Experiments and Observations by various Authors—Lambert's celebrated Memoirs—The Memoirs and Experimental Investigations of Coulombe—Hanstein's Researches—Theoretical and Experimental Inquiries by the Author—Barlow's Deductions and Experiments on Iron Shells.

173. The wonderful influence of Magnetism as a physical agent would necessarily lead to an investigation of the laws by which its operations are regulated. The first and most obvious step in such an inquiry would be the general law of change in the effective force of Magnetism, as the distance at which it acts is varied, or, in other words, to find according to what law two magnetic particles attract or repel each other magnetically, as the distance between them is increased or decreased.

But, before entering upon this question, it may not be unimportant to the student to review briefly the numerical and mathematical elements essential to the progress of such an investigation.

174. We have first to observe,—That when any two quantities are so linked together that one of them cannot be changed in any degree without some relative change taking place in the other, then the one quantity is said to vary in some particular ratio of the other, either *directly* or *inversely*.

Suppose, for example, the power of a magnet to *increase*, when that peculiar condition of its molecules, which we term magnetic, becomes *exalted*, or reciprocally to *decrease* when that condition becomes *depressed*, then the force is said to vary in some proportion of the magnetic intensity *directly*. In this case, the two quantities both increase or decrease together. Again, the magnetic condition being the same, suppose the attractive force to *increase*, when the distance of its action is *diminished*, or to *decrease* when that distance is *increased*. In this case, the force is said to vary in some proportion of the distance; inversely, since one of the quantities increases as the other decreases; or conversely, one decreases as the other increases. We may, however, as is evident, have a great variety of different relative proportions, according to which such changes may ensue. It might be, for example, that when we doubled the exaltation of the magnetic condition, the force of the magnet would be also doubled, or it might be quadrupled, or increased in any other direct proportion, in which case the force would be said to vary, as the first, second, third, &c., powers of the magnetic intensity, as the case may be; and this also applies to the several inverse ratios as it respects the force, and distance of its action.*

* Not to leave anything connected with these inquiries unexplained, we venture to remark:—

That the successive multiplication of any given number by itself constitutes what have been termed powers of that number. Take, for example, the number 4, and multiply it by 4; then we have, adopting the common arithmetical signs $4 \times 4 = 16$. We have here two factors, producing 16; hence 16 is said to be the second power of 4, usually called the square of 4.

In like manner, again multiplying by 4, we have $16 \times 4 = 64$, which, being the same as $4 \times 4 \times 4$, gives three factors; hence 64 is termed the third power of 4, commonly called the cube of 4, and so on.

Such powers are represented by a small figure, called an index, placed at the head of the given number; thus, we may write successive powers of 4 thus—

$$4^2,\ 4^3,\ 4^4,\ 4^5,\ 4^6,\ \&c.;$$

175. Taking the inverse or reciprocal proportions, as being in the present inquiry well adapted to further explanatory illustration, we have to observe,—First. That when the force decreases in precisely the same inverse proportion as the distances increase, or reciprocally; that is to say, if at *half* the distance the force be *twice* as great, at *one-third* the distance *three times* as great, and so on; then the force is said to vary in the inverse simple ratio, or first power, of the distance, since we take the simple numbers, 1, 2, 3, &c. to represent the increase of the force. Supposing, however, that

thereby showing that 4 is multiplied into itself 2, 3, 4, &c. times. We may observe here, that in taking the indexes in the reverse direction, 6, 5, 4, 3, 2, &c., we should fall back upon 1, and even upon zero or 0, and hence arrive at 4^1 and at 4^0, that is, 4 raised to the first power, and 4 raised to the power of nothing; so that 4 taken as a single factor may be considered as the first power of 4. With respect to 4^0, or any other number whatever, raised to the power of 0, its value is always unity or 1, as is seen in any of the ordinary works on Algebra. Taking a to represent any number whatever, we have hence the following series:—

$$a^0,\ a^1,\ a^2,\ a^3,\ a^4,\ \&c.$$

When we again revert to the number, from which any given power has been obtained, we are said to extract the 2nd, 3rd, 4th, &c., root, as the case may be. Thus, the third root of 64 would be 4, since, as just remarked, $4 \times 4 \times 4 = 4^3 = 64$, so likewise, the second root of 16 would be 4, since we have $4 \times 4 = 4^2 = 16$; the second root has been called the square root, the third root the cube root.

In like manner, we have the 5th root of $32 = 2$, since $2 \times 2 \times 2 \times 2 \times 2 = 2^5 = 32$.

These roots are often represented by a fractional index, that is, by dividing the index of the power by the index of the root we wish to extract. Thus the square or 2nd root of 3 to the first power may be expressed thus, $3^{\frac{1}{2}}$; the cube or 3rd root of 5, by $5^{\frac{1}{3}}$, the square root of the 5th power of 2 by $2^{\frac{5}{2}}$, and so on. In this sense we are said to raise the given number to the power of $\frac{1}{2}$ or $\frac{1}{3}$, or $\frac{5}{2}$, as the case may be.

Commonly, such roots are represented by the index of the given root, placed within the sign $\sqrt{\ }$, thus, for the cube root of 3, we write $\sqrt[3]{3}$, for the 5th root of 2 $\sqrt[5]{2}$. In thus representing the square root of any given number, the small figure for the index is commonly omitted; thus, for square root of 9, we write simply $\sqrt{9}$.

at *one-half* the distance the force becomes *four times* as great, at *one-third* the distance *nine times* as great, and so on. In this case the force would be said to vary in the inverse duplicate ratio, or second power of the distance, since, to represent numerically the increase of the force, we must multiply the numbers 1, 2, 3, &c., into themselves, taking their second powers or squares. In a similar way, cases may arise in which the increase or decrease of the force is such as to require the third power or cubes of the numbers 1, 2, 3, 4, &c., to complete the proportion. This would arise when, at half the distance, the force had increased 8 times, at $\frac{1}{3}$ the distance, 27 times, and so on. In this case the law of the force is said to be as the cubes of the distances inversely, or in the inverse triplicate ratio of the distances; and thus we may continue for any other powers of the numbers 1, 2, 3, &c., so as to express laws of force in the inverse ratio of the 4th, 5th, 6th, or any other powers of the distance, did such forces exist.

A similar reasoning applies to forces increasing or decreasing in any inverse proportion *less* than that of the mere distance, as in the case of a force becoming doubled at $\frac{1}{4}$ the distance; trebled at $\frac{1}{9}$ the distance. In this case the force would be said to vary inversely as the square roots of the distance, since we must take the square roots of the numbers, 1, 4, 9, &c., to fulfil the proportion. In this way we express the law of force for any other roots of the distances, such as the cube, or 3rd root, the 4th root, &c.; and since these roots are mathematically denoted by fractional indexes, we may consider such forces as being in the inverse ratio of the $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c., powers of the distances.

176. We may further extend this inquiry to cases of roots of the simple or other powers, such, for example, as the square root of the cube of the distance, being, as expressed mathematically, the cube of the distance raised to the power of $\frac{1}{2}$. An inverse proportion of this kind has been termed "sesquiplicate," and would apply to a case in which, by

decreasing the distance to $\frac{1}{3}$, $\frac{1}{5}$, &c., the force becomes about 3 times and 5 times as great, or very nearly. In like manner we may obtain forces varying in the inverse ratio of the square roots of the 5th powers of the distances, termed, "sesquiduplicate," and which applies to a case in which, by reducing the distance to $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c., the force becomes increased between 5 and 6 times, and between 15 and 16 times, and 32 times respectively. In this way almost any observed experimental results, demonstrative of any particular law of force, may be mathematically represented.

177. The particular inverse ratio comprised in a series of experimental numerical results of this kind may be easily discovered by a slight inspection, since the forces multiplied by the simple or some other power of the corresponding distances should, in each particular case, give the same product. Thus, if at distance 12 the force were 8; at distance one-half or 6 the force became 16, we have in this case $12 \times 8 = 6 \times 16 = 96$, a simple inverse proportion; but if at distance 12 the force were 8, and at distance 6 the force became 32, then to obtain a coincident product, we must take the second powers or squares of the numbers 12 and 6, and we should then have $12^2 \times 8 = 6^2 \times 32$, or $144 \times 8 = 36 \times 32 = 1152$. In the case of direct proportion the products are differently circumstanced.*

178. We have been desirous to place this question (178)

* A complete apprehension of these practical researches and proportions being essential, the following numerical examples may not be altogether uncalled for :—

Let the distances be taken in some unit of measure, say tenths of an inch, and the corresponding forces in any other unit of measure, say degrees of an arc, as in the way described, Parts I. and II. sec. 128, and represented, Fig. 71, Frontispiece.

Suppose as a first example, we had obtained the following results :—

At distances..........	12·	6·	4
The forces are	5	10	15

Here we have the inverse simple proportions,—5 : 10 :: 6 : 12, and 5 : 15 :: 4 : 12, and 10 : 15 :: 4 : 6. Product of distances and forces = 60.

B 2

before the student in a simple and intelligible form, principally on account of the great importance of such inquiries

As a second example, let the results be—

At distances..........	12·	6·	4
Forces..............	2·	8	18

Here we have an inverse duplicate ratio, or square of the distance, furnishing the proportions—

$$2 : 8 :: 6^2 : 12^2, \text{ and } 2 : 18 :: 4^2 : 12^2, \text{ and } 8 : 18 :: 4^2 : 6^2;$$

that is $2 : 8 :: 36 : 144$, and $2 : 18 :: 16 : 144$, and $8 : 18 :: 16 : 36$.

Product of forces by squares of the distances, 288.

As a third example, suppose the experimental numbers were—

At distances..........	16 and	4
Forces are	2 ,,	128

This would furnish a proportion inversely as the cube of the distance, and we should have—

$$2 : 128 :: 4^3 : 16^3; \text{ that is } 2 : 128 :: 64 : 4096.$$

Product of forces by cubes of the distance, 8192;

and so on for other changes of distance, or any other powers.

Let now the results be—

At distances..........	16 and	4
Forces	3 ,,	6

In this case we should have a proportion in the inverse ratio of the square roots of the distances, and we should obtain the inverse proportion—

$$3 : 6 :: 4^{\frac{1}{2}} : 16^{\frac{1}{2}}; \text{ that is } 3 : 6 :: \sqrt{4} : \sqrt{16}, \text{ or } 3 : 6 :: 2 : 4;$$

Product of forces by square root of the distances $= 12$.

Again, let distances and forces be thus—

At distances..........	27 and	8
Forces	6 ,,	4

Here we have the inverse proportion of the third or cube roots of the distances, and we obtain—

$$6 : 4 :: 27^{\frac{1}{3}} : 8^{\frac{1}{3}}; \text{ that is } 6 : 4 :: \sqrt[3]{27} : \sqrt[3]{8}, \text{ or } 6 : 4 :: 3 : 2.$$

Product of forces by third roots of distances $= 12$.

And so on for any other roots.

The following are examples of sesquiplicate and sesquiduplicate inverse proportions, being fractional powers or roots of powers.

Suppose that—

For distances............	12	6	4
Forces were	5	14·2	26

to the general progress of science and theoretical knowledge. Thus Newton demonstrates, in his great work, "The Principia," that if the particles of common matter act on each other with a force varying in the inverse proportion of the

Here the forces are in inverse proportion to the square roots of the cubes of the distances, or in inverse sesquiplicate proportion, and we obtain such a proportion as this, for distances 12 and 6.

$$5 : 14{\cdot}2 :: 6^{\frac{3}{2}} : 12^{\frac{3}{2}};\ \text{that is } 5 : 14{\cdot}2 :: \sqrt{6^3} : \sqrt{12^3},\ \text{or}$$

$$5 : 14{\cdot}2 :: \sqrt{216} : \sqrt{1728},\ \text{or } 5 : 14{\cdot}2 :: 14{\cdot}7 : 41{\cdot}5 \text{ nearly.}$$

Product of forces by square roots of cubes of distances $=$ 208 nearly.

A similar proportion is evident for the remaining forces and distances.

As a last example—

Let distances be..........	12	6	3
And forces..............	4	22·5	128

Here the forces are in an inverse sesquiduplicate proportion, or in an inverse proportion to the square roots of the 5th power of the distances, and we obtain for distances 12 and 6 the following:—

$$4 : 22{\cdot}5 :: 6^{\frac{5}{2}} : 12^{\frac{5}{2}},\ \text{or } 4 : 22{\cdot}5 :: \sqrt{6^5} : \sqrt{12^5};\ \text{that is}$$

$$4 : 22{\cdot}5 :: \sqrt{7776} : \sqrt{248832},\ \text{or } 4 : 22{\cdot}5 :: 88{\cdot}5 : 499 \text{ nearly.}$$

Product of forces by square roots of 5th powers of distances $=$ 1996 nearly.

The numerical operations in these examples have been taken as the numbers stand, without regard to any further reduction; but, as will be evident on examination, the arithmetical processes may be made smaller by taking the ratio of the distances and forces, instead of the distances and forces as given by experiment, when that can be done conveniently.

In cases of direct proportions the products are obtained by a method the reverse of this. We then multiply the terms crosswise, as it were. Suppose, for example, in three experiments, in which the magnetic intensity varied, we had obtained the following:—

Magnetic intensity	1	2	3
Force	4	8	12

In this case of direct proportion the magnetic intensity is not multiplied into its corresponding force, but into the force of the intensity with which it is compared. Thus, comparing intensity 1 with intensity 3, we have $1 \times 12 = 4 \times 3 = 12$; or, comparing intensity 2 with intensity 3, we have $2 \times 12 = 8 \times 3 = 24$, passing on crosswise of the table. In fact, we have here $1 : 3 :: 4 : 12$, or $3 \times 4 = 1 \times 12$; also $2 : 3 :: 8 : 12$, or $3 \times 8 = 2 \times 12$; and this applies to direct ratios involving powers or roots, as before.

squares of their distances, then the sensible action of hollow or solid spheres on each other will be the same as if all the matter of which they consist were collected in their centres, and that a particle placed anywhere within them would be in equilibrio, and not tend to move in any one direction; which he shows could not be the case under any other law of force. So, likewise, if the hidden source of electrical and magnetic phenomena be, as many suppose, a subtile elastic fluid of a specific kind, then, as was observed by the Honourable Henry Cavendish, in some of his manuscripts, such a fluid would be similar to air, if the repulsive force between the particles were inversely as any power of the distance greater than 3, only that the elasticity would be inversely as the $n+2$ power of their distances, or as the $\frac{n+2}{3}$ power of the density of the fluid; n being any number exceeding 3. But if n be equal to or less than 3, such an elastic fluid would be very different from that of air. Again, the times in which the planets revolve about the sun are in a sesquiplicate ratio of their distances from the centre, and not in a duplicate ratio. Hence, observes Cheyne, they "cannot be carried about by an harmonically circulating fluid," as was supposed by some of the ancient philosophers.

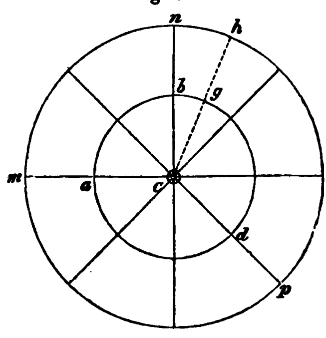
We may further remark in respect of Magnetism, that the force by which a magnetic needle is drawn towards its meridian when deflected from it (21), or towards a magnet, increases as the sine of the angle of the obliquity of action directly. Hence, as observed by Professor Robison, we cannot pretend to explain the action of a magnet by the impulsion of a stream of fluid, or by pressure arising from the motion of such a stream; for in this case the pressure on the needle must have diminished directly, as the square of the sine of the angle, at which the magnetic force operates on the needle. For example, the force at a right angle, or 90 degrees, should be 4 times greater than the force at an angle

of 30 degrees, whereas it is found to be only twice as great; being simply as the sines of the angles. It is, therefore, by the determination of the laws of such forces that we are enabled to advance our knowledge of the powers of nature.

179. Beside these preliminary explanations (173), there remain still to be considered one or two additional points equally essential to an intelligible and plain view of the questions involved in such inquiries, and the real sense in which we are to accept such expressions of the law of variation of certain forces as we have just cited (173).

To suppose any effect to be as the square or cube of its cause, either directly or inversely, is to suppose the effect to proceed partly from the cause and partly from nothing. For there is no axiom in Physics more evident than that which assigns between cause and effect a simple relation; any expression, therefore, which represents a force as being in any inverse ratio of a power of the distance greater than unity, may at first appear to involve an absurdity. We may hence infer that, when by experiment we have arrived at such a conclusion, the result is either a mixed result, compounded of two or more conjoined actions, or it is a result resolvable into some elementary condition of a simple kind, depending on the peculiar kind of agency upon which the exhibition of force depends. Take, for example, the following case of a central force, or emanation of any kind, extending its power in all directions into space, and hence becoming weaker in proportion to the surface of the spaces over which we may suppose it to expand. Let *c* (Fig. 98) represent such a central action; suppose, for example, a central source of light considered as luminous matter by way of illustra-

Fig. 98.



tion. Let *a b d*, *m n p*, be two great concentric circles, representing two concave hemispherical shells, whose centre *c* is the point of illumination, and whose radii *c a* and *c m* are to each other as 1 : 2; or, in other words, that point *n* is twice as far from the centre *c* as the point *b*. If in this case we take any two homologous segments, *b g*, *n h*, of these shells, it is clear that the segment *n h* will have four times the area of the interior similar segment *b g;* because the superficial areas of such shells will be in proportion to the squares of the diameters of their great circles *m n p*, and *a b d*, and these are supposed in this case to be as 1 : 2; so that the quantity of luminous matter (supposing light to be a material agency) which has emanated from the centre *c*, and fallen upon these shells, will in the outer shell *n* become distributed over 4 times the space, it would occupy, on the interior shell *b*; that is to say, in any one point, there will be only ¼ the quantity of light: hence the illumination of the arc *n h* will only be ¼ of the illumination of the arc *b g;* that is to say, the illumination will be directly, as the quantity of light in a given space, a simple relation of cause and effect. When, however, we refer this effect to the distance from the centre *c*, we perceive that the distances being as 2 : 1, the illumination of the whole of each shell is as 1 : 4. And thus light as a physical agency has been said to vary in intensity in the inverse ratio of the squares of the distance from the centre, in the way just explained (174); but the fact is, that the illumination of an equal area in each shell is directly as the quantity of the agency producing it.*

180. Again, in the cases of such powers as those of Magnetism and Electricity, we have to consider many conjoint

* The term intensity is really inapplicable here: it is a term, in science, only distinctive of quality, or of different states or degrees of power of the same agent; as when we say the heat of a red-hot iron is more intense than the heat of boiling water, or that moonlight is less intense than the light of the sun. Taking a particle of light from the same source, we have no reason for supposing it in a different state of intensity at different distances from the centre of illumination. If such

actions (33, 37). A magnet and common iron only operate on each other through the medium of a reciprocal induction (35); (38) when we change the distance of their action, we change at the same time the original condition or quantity of force in operation; so that we may conceive the total force of attraction to depend on the force induced in the iron (33) conjoined with the reciprocal induction on the magnet (37); and it may be here remarked, that in the apparent anxiety of philosophers to bring such forces indiscriminatively under the common law of gravity, and other central forces, they have probably encouraged a rather hasty generalization. All the forces in nature are not necessarily central forces, they may arise out of peculiar conditions of common matter, of which we have as yet but an indistinct notion, and be exerted between given points in determinate directions only, as appears to be indicated in Fig. 17, p. 24, Parts I. and II.; we have yet to learn, therefore, whether the force of Magnetism comes under the general conditions of ordinary central forces or not.

181. Newton, in his learned and profound work, "The Principia," considers magnetic force as being very different from that of gravity:—"The magnetic attraction is not (he says), as the matter attracted; some bodies are attracted more by the magnet, others less; most bodies not at all. The power of magnetism in one and the same body may be increased and diminished, and is sometimes far stronger for the quantity of matter than the power of gravity; and, in receding from the magnet, decreases not in the duplicate, but almost in the triplicate proportion of the distance, as nearly as I could judge from some rude observations."—*Book* iii., *Prop.* 6.

In the 23rd proposition of the Second Book, sec. 5, Newton imagines that, in magnetical bodies, "the attractive

were the case, both the quantity of light in a given space, and its intensity also, would change with the distance, and the illumination would then decrease much faster than that of the inverse squares of the distances.

virtue is terminated nearly in bodies of their own kind that are next them." "The virtue of the magnet," he says, "is contracted by the interposition of an iron plate, and is almost terminated at it, for bodies further off are not so much attracted by the magnet as by the iron plate." The experiments we have adduced (38), Fig. 29, have immediate reference to this observation.

182. Of the early experiments instituted with a view of determining the laws of magnetic forces, we have to notice first those of Hawksbee, printed in the Transactions of the Royal Society for the year 1712, vol. 27. A short needle, one inch in length, being poised on a fine point, fixed in the centre of a graduated quadrant, a natural magnet was placed, with one of its poles within certain measured distances of the centre of the needle, and the corresponding deviations of the needle from the meridian, noted in a way similar to that described, Parts I. and II., page 121, sec. 134, Fig. 82. The results have not generally been considered very satisfactory or regular; it is, nevertheless, worthy of remark, that, taking the tangents of the angles of deviation, corresponding to distances, which may be considered as very great in respect of the length of the needle, on the principles already laid down (134), then Hawksbee's results will be found consistent with each other, and, according to a law of force, varying in the inverse sesquiduplicate ratio (176) of the distances, as shown in the following analysis of the results:—

Distance in inches ..	12	18	24	30	36	42	48	54	60
Angles of deviation ..	69	43-30	24	13-30	8-45	5-30	3-50	3	2-30
Tangents of deviation .	2·6	·948	·445	·240	·153	·096	·067	·052	·043

Taking these tangents as representing the forces, they will be found all very nearly in the inverse proportion of the square roots of the 5th powers of the distances, in some cases precisely.*

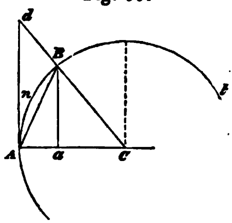
* In such experiments as these, we must recollect, that angles do not enter into ordinary calculation, except through the medium of certain lines taken to represent them. These lines have been termed sines,

183. Dr. Brook Taylor, in following up this method of experiment, was led at first to infer, " That the power of

tangents, secants, &c. It may not be out of place to recall briefly to the student's attention the nature of the two lines with which we are here especially concerned; viz., the tangent and sine of an angle.

Every angle A C B, Fig. 99, is measured by an arc A n B of a circle A B t, contained between its sides, and described from its point or vertex C as a centre. The line A B joining the extremities of the arc being called the chord of the arc.

Fig. 99.



Now a perpendicular line B a, drawn from the extremity B of the radius C B, forming one of the sides of the angle, directly upon the other side C A, has been termed the *sine of the angle* A C B; the length of this line, as is evident, will be greater or less as the angle A C B is greater or less.

Again, the line A d drawn perpendicular to the radius or side C A, upon the extremity A, and meeting the side C B, continued on to meet A d in the point d, has been termed the tangent of the angle A C B. This line also will increase and decrease with the magnitude of the angle.

If the radius C A be taken as unity, and be supposed to be divided into any number of parts, say 1000, or 10·000, or 100·000, then these lines, as applying to a given angle, will be found to contain a certain number of these parts. Thus, if we call radius A C = 1, or unity, and divided, say into 100 parts, then if the angle A C B be 30°, the sine B a will be one-half the radius A C, will contain 50 of these parts, and will be represented by ·5; the tangent A d will, in this case, contain about 57 parts, and will be represented by ·57. Now it is these numbers, as calculated and arranged in tables, with which we have to do, and not immediately with the angles themselves.

As all these lines, and the principles of their construction and use, are to be found in our elementary mathematical works, we will not longer dwell on them here. (*See* " Rudimentary Plane Trigonometry," p. 8.)

Comparing distances 12 and 24, which are as 1 : 2, we have

$2·6 : ·445 :: 2^{\frac{1}{2}} : 1 :: 5·65 : 1$, or $5·65 \times ·445 = 2·6$, or $2·5 = 2·6$ nearly.

Take again distances 12 and 18, which are as 2 : 3, here we have

$2·6 : ·948 :: 3^{\frac{1}{2}} : 2^{\frac{1}{2}} :: 15·5 : 5·65$, or $5·65 \times 2·6 = 15·5 \times ·948$;
$= 14·6$ nearly.

In a similar way, the products for distances 30 and 60 are $·240 = ·246$;

magnetism does not alter according to any particular law of the distances, but decreases much faster in the greater distances than in the near ones."* By subsequent and similar experiments, however, instituted by Whiston, Brook Taylor, and Hawksbee, conjointly, "the attractive power of the loadstone was found in the inverse sesquiduplicate ratio of the distances" (176). In these experiments they measured the forces by the sines of half the arcs of deviation, to which they endeavour to show the "force is always proportional."

184. About this period, experimental philosophy began to make considerable advances in Holland, and to excite very general interest; we consequently find the Dutch philosophers contributing largely to our knowledge of this branch of physics. The celebrated Muschenbroek instituted some experiments in 1724, the object of which was to find experimentally the law of magnetic attraction by the method of weights (125). Having suspended a spherical magnet from one arm of a balance, and poised it by weights suspended from the opposite arm, he placed a similar magnet immediately under it, and then proceeded to find the additional weights requisite to balance the attractive force at given distances between the opposed poles. These distances were regulated by raising or depressing the beam of the balance by means of a line passing over a pulley, and by which it was supported. The numerical results of the experiments were considered so unsatisfactory, as to lead to the conclusion that "no assignable proportion" exists between the forces and the distances, whether of attraction or repulsion, and "that magnets are indeed very surprising bodies, of which we know but little."†

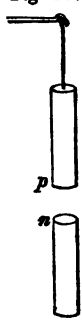
for distances 12 and 36 we have $2{\cdot}4 = 2{\cdot}6$, which may in each case be considered as sufficiently near.

The greatest inequality appears to be for distances 18 and 54, being $\cdot 948 = \cdot 814$; all the others approach as nearly an inverse sesquiduplicate ratio as can be expected from the nature of the experiment.

* Phil. Trans. for 1721. † *Ibid.* for 1725.

185. In the "Introduction to Natural Philosophy,"* however, by Muschenbroek, we find the subject more satisfactorily investigated and pursued, the results being such as to demand very especial attention. The method of experiment did not materially differ from the former. The following cases comprise the amount of the investigation:—

Fig. 100.

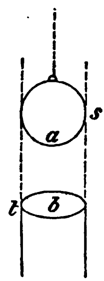


First case.—Attractive force between a magnetic and iron cylinder. In this experiment a cylindrical magnet, *p*, Fig. 100, two inches in length, and about ·95 of an inch in diameter, was suspended over an equal cylinder of soft iron, *n*, and the attraction at different distances, *p n*, noted. The results were as follow:—

Distance in tenths of an inch	6	4	3	2	1	0
Force in grains	3	5	6	9	18	57

Muschenbroek observes, on this experiment, that the attractive forces are inversely as the intercepted cylindrical spaces, *p n*, that is, inversely as the distances (174), the law is uniform up to contact, or nearly so.

Fig. 101.



Second case.—Attraction between a spherical magnet and a magnetic cylinder. In this experiment a spherical magnet, *s*, Fig. 101, was suspended, with its north pole, *a*, downward, and a cylindrical magnet, *t*, of the same diameter, viz., ·95 of an inch, placed with its south pole, *b*, upward, immediately under it, the poles being in one straight line. The following were the results:—

Distance in tenths....	6	4	3	2	1	0
Force in grains	21	34	44	64	100	260

We may conceive, says Muschenbroek, "The sphere (*s*) to be in a hollow cylinder (*t s*), and let down at various distances (*a b*) from the cylindrical magnet. Then, considering the intercepted spaces (*t s*), the attractions will be found in the inverse sesquiplicate ratio of these

* Translated by Colson, in 1744, for the use of the Universities.

spaces, that is, inversely as the square root of the cubes of the spaces" (176). In referring the distances, however, to the near point, *a*, of the sphere, still the law does not very materially differ from the former case, being approximately in the inverse simple ratio of the distance, *a b*.

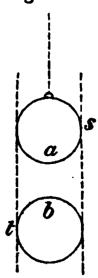
Third case.—Attraction between a magnetic sphere and a cylinder of iron of the same diameter = ·95 of an inch. In this experiment, a cylinder of iron, *b*, Fig. 101, was placed under the north pole, *a*, of the spherical magnet, *s*, this cylinder being the same as used in the first case. The following were the results:—

Distance in tenths	6	4	3	2	1	0
Force in grains	7	15	25	45	92	340

Muschenbroek, in referring the forces to the intercepted spaces (*t s*) as before, deduces the same law as in the former case; if, however, we refer the forces to the distance, *a b*, we find no regular law. The first three forces are inversely as the squares of the distances, or very nearly; the forces corresponding to distances 4 and 2 are in the inverse sesquiplicate ratio of the distances; this is also evident at distances 6 and 1. At the smaller distances, 2 and 1, the force is inversely as the simple distance, very nearly. At distances 6 and 2 no law is apparent.

Fourth case.—Attraction between a magnetic and iron sphere of equal diameters. In this experiment, a globe of iron, *b*, Fig. 102, was placed immediately under the north pole, *a*, of the suspended spherical magnet, *s*. The forces and distances in this case stood thus:—

Fig. 102.



Distance in tenths ..	8	6	4	3	2	1	0
Force in grains......	1	3·5	9	16	30	64	290

It is remarked by Muschenbroek, in this case, that if "we suppose both the spheres to have been included in a hollow cylinder (*t s*), and to be removed from one another at various distances, and the

intercepted hollow spaces ($t\ s$) to be considered; then we find the law in a reciprocal biquadratical ratio of the intercepted spaces; that is, inversely, as the 4th powers of the intercepted spaces (174). If, however, we refer the forces to the nearest points of distances, $a\ b$, we have all sorts of inverse proportions for the law of the force; thus, the forces at distances 8 and 4 are inversely as the 3rd power, or cubes of the distances, or very nearly; at distances 8 and 1 they are, inversely, as the second power or square of the distance; and this law holds approximatively for the forces at distances 6 and 4, for 6 and 3, for 6 and 2, and 4 and 3, in which last case it is exact.

At distances 8 and 2 the forces are as the square roots of the fifth powers of the distances inversely (176). Taking the near distances, 2 and 1, we have the forces nearly in the simple inverse ratio of the distances; whilst, at the distances 6 and 1, as also 4 and 2, the law approaches the inverse sesquiplicate ratio of the distance, that is, the square root of the cubes of the distances (176).

186. These results are not only curious, but they are really calculated, when properly considered, to throw very considerable light on the nature and mode of operation of magnetic force, as we shall presently see; and it is to be greatly regretted, that more attention has not been commonly bestowed on them. Muschenbroek's researches are usually quoted without due precision, and without any adequate explanation of the author's own peculiar deductions; they have been also not unfrequently treated lightly as furnishing no solid information whatever, from assumed imperfections in the nature of the experiments themselves.

187. We may infer, by the second and third cases, in which the force at contact, between a cylindrical and a spherical magnet, and the force between a similar cylinder of iron and the same spherical magnet is given, that when actually touching, a magnet does not attract another magnet so forcibly as it attracts simple iron, the force being,

in the one instance 260 grains, in the other 340 grains. The force, however, between the two magnets, diminishes less rapidly as the distance is increased, and would hence begin from a more remote point.

188. In the "Essai de Physique," printed at Leyden, in 1751, Muschenbroek more expressly refers to his early experiments in 1724, and although they led to no general conclusions, yet they furnish most important examples of the operation of magnetic forces under the given conditions. The following table, for example, contains the results of a series of observations on the force of two spherical magnets of very unequal diameters, opposed to each other at dissimilar poles, as in Fig. 102, one of the magnets being 6·5 inches in diameter, the other 1·5 inches.

Distance in lines—																
54	50	45	28	21	12	10	9	8	7	6	5	4	3	2	1	0
Force in grains—																
1·75	2·25	2·75	9	12	26	31	34	36	39	44	48	59	68	89	132	310

Many of these forces approach the inverse sesquiplicate ratio of the distances. It is, however, observed by Muschenbroek, that, from the unequal diameters of the spheres, "it is not easy to calculate the intercepted spaces: this led me to try the forces between a spherical magnet and a ball of iron, each ·95 of an inch in diameter." The attractions, as thus obtained, have been already given. Fourth Case (185).

The following are the results of observations on the repulsive poles of two magnets, and of two pieces of magnetic iron.

REPULSIVE FORCE OF TWO MAGNETS.

I.

Distance in lines	48	27	12	11	10	9	8
Force in grains	6·5	13	30	32	32	33	34

II.

Distance in lines	12	10	6	5	4	0
Force in grains	24	24	25·5	27·5	29	40

REPULSIVE FORCE OF MAGNETIC IRON.

III.

Distance in lines ..	12	10	6	5	4	3	2	1	0
Force in grains ..	3·5	4·25	7·5	7·75	8	10·5	14·5	14	Attn.

It is important to observe, in these last experiments, that, in the first forces and distances, the force is as the distances inversely, after which the increase of the repulsion decreases, and the force changes into attraction. We have thought it right to select these cases for consideration. For, notwithstanding that they led at first to the conclusion "that magnets are surprising bodies, of which we know but little," they will, nevertheless, be found to have a most important bearing on the question of magnetic force.

189. Martin, who followed Muschenbroek's method of experiment, found that for certain small distances the force of a magnetic pole, on a bar of soft iron, was in the inverse sesquiplicate ratio of the distance. In these experiments a plate of wood, of a thickness equal to the required distance, was interposed between the suspended magnet and iron. The magnetic pole being allowed to rest on the wood, and to which it would become drawn by the reciprocal attraction between the iron and magnet, small weights were then added to the scale-pan attached to the opposite arm of the balance, until the magnet pole became raised off the wood. The actual force and distances were as follows:—

Distance in inches............	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$
Force in grains	156	58	28

It will be immediately perceived that these forces are inversely as the square roots of the cubes of the distances very nearly. Taking the distances as the numbers 1, 2, 3, we have $1\times156=2^{\frac{3}{2}}\times58=3^{\frac{3}{2}}\times28$ (177); the differences in the products, viz., 156, 164, and 145, are not so great as to place them without the limit of a fair approximation, especially when we take into account the difficulty of such experiments. If at distance $\frac{1}{2}$ the result had been 56 grains instead of 58, and at distance $\frac{3}{4}$ it had been 30 grains instead of 28, then the ratio would have been exact. The experiments appear to have been carefully made.*

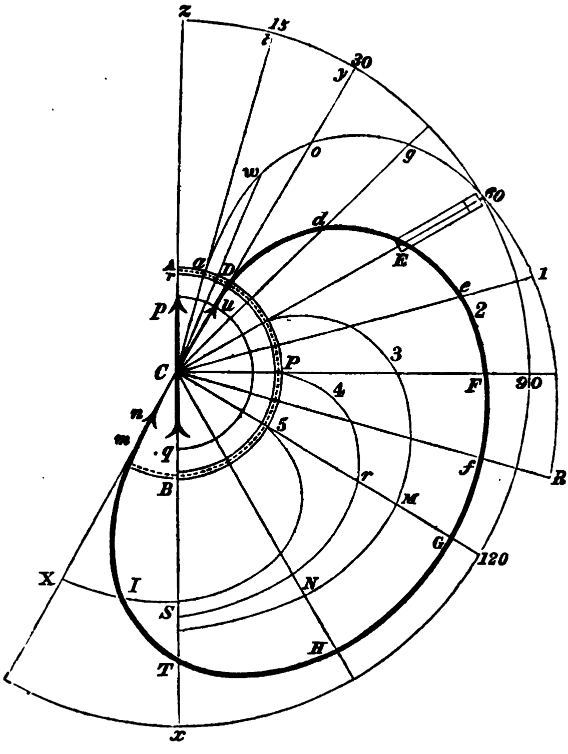
* "Philosophia Britannica," London, vol. i. p. 47.

190. Mayer, in an unpublished paper read before the Royal Society of Gottingen, in 1760, found the force of magnetic attraction to correspond with the general law of gravity. A deduction also arrived at by Michell, who says, in his capital treatise on Artificial Magnets, published in 1750, that in all the experiments of Hawksbee, Brook Taylor, and Muschenbroek, the force may really be in the inverse duplicate ratio of the distances, proper allowance being made for the disturbing changes in the magnetic forces (180) so inseparable from the nature of the experiment. He is hence led to conclude that the true law of the force is identical with that of gravity, although he does not set it down as certain. It is to be greatly regretted, as observed by Lambert, that the Royal Society of Gottingen did not publish Mayer's researches on this important physical question.

191. In the 22nd volume of "Histoire de l'Académie Royale des Sciences," Berlin, 1776, we find two beautiful memoirs on this subject by M. Lambert, which were considered by Dr. Robison as worthy of Newton himself. It is, therefore, imperative, in a treatise of this kind, to put the student in possession of the substance of these papers, more especially as a detailed and clear exposition of Lambert's experiments has seldom, if ever, appeared in our elementary works on this branch of science. In his first memoir the author endeavours to determine two very important laws of magnetic action; one relating to the change of force as depending upon the obliquity of its application, the other as referred to the distance. M. Lambert's course of experiment was as follows:—

A small needle, $p\ q$ (Fig. 103), about an inch in length, being poised on a fine centre C, fixed in a plane of wood, a circle A P B, one-half of which only is in the figure, was described about the needle, and divided into 180 degrees, both on the east and west side of the magnetic meridian x C z; the central or north point A of the semicircular arcs

Fig. 103.



being marked zero; the plane supporting the needle was made to turn about the centre C, so as to adjust the zero point A exactly in the line of the needle. This preparation made, Lambert placed a small magnet E, of a cubical figure, the same length and breadth as the needle, and one-half the thickness, in various positions, E, *e*, F, *f*, G, &c., about the needle, so as to deflect it from its meridian by a given angular quantity. We already know (134, 135) that in bringing a magnet near a compass needle in this way, the needle changes its position, so that by varying the position of the

magnet, we may produce any declination we please; we may also give the magnet E an infinity of different positions, or may change its place as from D, F, G, H, &c.; and hence may find such positions or points for its action as will all produce the same degree of declination in the needle. Now M. Lambert limited the precise position of the magnet in any particular point, E, to that in which the axis of the magnet and its south pole were directed to the centre C of the needle, as in the line E C; and he selected given declinations of the needle from 10 to 10 degrees on the west side of the meridian, and from 15, 30, 60, 90, up to 120 degrees on the east side. Having found all the points, as, for example, D *d*, E *e*, F *f*, G, H, I, &c., in which the magnet E, thus circumstanced, gave the same amount of declination, say 30 degrees, he proceeded to trace a curve, D E F G H I *m*, through all these points, and by means of which he endeavours to assign the law of force as directed to the centre C.

192. For the better tracing the various circles and curves, the plane on which this operation was performed was covered with fine paper. The figure is about ¼ of the size of the actual experiment, and as the curves on each side of the meridian *z* C *x* were found to be nearly similar, those on one side only are given, in order to avoid complication. In Fig. 103 then, C is the centre upon which the needle plays, *x* C *z* is the magnetic meridian. The angles A C *a*, A C D, A C E, A C F, A C G, are angles of 15, 30, 60, 90, 120 degrees, being the respective constant declinations producing the curves 1, 2, 3, 4, 5. Thus the magnet being in curve 2, the declination of needle was always 30 degrees. When in curve 3, it was always 60 degrees, and so on. By this arrangement an equilibrium is obtained between three forces: viz., the magnetic force of the needle; the directive force, or unknown power by which it is drawn to the meridian A B; and the force of the magnet E by which the needle is deflected or drawn from its meridian.

193. In comparing the curves thus obtained, Lambert only assumes, what in fact is shown by all experience, that the magnetic force decreases when the distance at which it operates increases. In estimating the element of distance, he finds it sufficient to take the distance between the extremity E of the magnet and the centre C of the needle. So that if it be merely required to know if the force of the magnet has been more or less great in one point than in another, as, for example, in points E and F, then the right lines C E, C F will be sufficient for that purpose, and the force of the magnet may be taken as being less as these lines are longer.

194. With a view to simplify our conceptions of M. Lambert's investigations, we will confine our references principally to one of the curves which he traced, viz., to the curve No. 2, corresponding to a deflection of 30 degrees, and which caused the needle, $p\,q$, to assume the direction n C u, making with the meridian, z C x, the angle z C $y = 30$ degrees. It may be here observed, that if we take, on either side of the radius, C G, any two points, F H, making equal angles, G C F, G C H, with that radius, and suppose the magnet to be in F, and attracting the north pole, p, of the needle with a force $= p$, and repelling the south pole, q, with a force $= q$, then we have only to place the magnet in H, and it will reciprocally employ force $= p$, to repel the south pole, and the force $= q$ to attract the north pole, that is to say, the distances G H and G F being equal, the position of the needle would not vary; and reciprocally, in order not to vary, these distances must be equal. The curve, D E F G H I m, therefore is similar to itself on each side of the right line C G, so that C G is an axis or diameter of that curve, and divides it into two similar and equal parts, that is, supposing a perfect resemblance and equality of force in both poles of the magnet. Mr. Lambert calls this axis, C G, a transverse axis or diameter, because it passes through the centre at right angles to the deflected position of the needle. Thus, when the

magnet E is in the curve E G H, just mentioned, the deflection being 30°, the position of the needle is the line *m* C D, and the axis is C G, and so for any other curve; thus, when the deflection is 60°, and the needle is in the line C E, then the axis of the curve is C N, being always at right angles to the direction of the needle. We may further observe, that all the curves extend themselves from the centre up to the points by which their respective diameters pass, as at X S N G R.

195. These experimental conditions of Lambert's investigations being understood, we may proceed to his analysis of them; and first, as relates to the change of force liable to occur from a greater or less degree of obliquity in the action of magnetism on the needle, considered as a lever, a most important element in the progress of such inquiries. Assuming, as we have just shown (194), that it requires everywhere the same effective force to retain the needle at the same declination, we might conclude conversely, that for the same degree of declination the distance should be always the same; but such is evidently not the case, since the points D E F G, &c., in curve No. 2, are all at different distances from the centre C, hence all the force of the magnet E cannot be everywhere exerted; some compensation between the force and distance must hence arise, if the needle at different distances is to remain in the same position. Now, we may observe that in different points of a given curve, D E F G H, the action of the magnet E is more or less oblique upon the needle *p q*; thus, the needle being retained in the line *n u*, at a deflection of 30°, the angle of obliquity at point E is E C D, at point F it is F C D, at point H it is H C D; that is to say, the obliquity of the action increases with the distances. In order, therefore, that the needle should remain stationary, the decrease of the force due to the increase of distance should be exactly the same as decrease of power arising from the increased obliquity of the action. To determine the law of the change of

force from obliquity, Lambert calls to his aid the polar or magnetic force by which the needle is drawn toward the meridian, and which also acts obliquely upon the needle, whenever we deflect it from its meridian. Thus the needle, *p q*, being drawn from its meridian into the line *n u*, the oblique action of the polar force is the angle *z* C *y*. To distinguish in certain cases the oblique action of the magnet E from this last obliquity, he calls the angles of obliquity of the magnet E angles of incidence. Thus, angles E C D, F C D, &c., are angles of incidence as regards the obliquity of magnetism in the action of the magnet E on the needle. If the law of the variation of the force as regards a change of distance were really known, we could easily determine the law of the increase or decrease of force as depending upon obliquity of action; for the effect depending on this obliquity of incidence would be in the same curve in an inverse ratio of the force, in order that the compound resulting effect might retain the needle in the same position; but Lambert had not determined this law, and is hence led to another method by taking into consideration the action of the polar force on the needle.

196. To determine the effect of obliquity, considered as depending upon the angle of obliquity, that is, as being some function* of that angle, Lambert took two equal distances, C *d* and C *r*, in which the absolute force of the magnet, independent of obliquity, might be considered the same. We may here observe, that when the magnet is in point *d*, the needle is found in direction C *u*, being, by the experi-

* This term *function* is in very common and accepted use in physico-mathematical science. It is employed to express, either algebraically or otherwise, any quantity whose value depends upon that of another. Thus the extent of the circumference of a circle will depend on the length of the radius of the circle. The circumference is hence said to be a function of the radius. In the present case the effective force of the magnetic power will depend upon the angle of incidence. It is hence said to be a function of that angle; so that we have to find what is the actual value or relation of this function to the magnetic power.

ment for that point, deflected 30°. The angle of incidence d C u is therefore 15°, and the obliquity of the polar force is the angle z C y=30°. Again, the magnet being in r, the needle is in direction C F, being by the experiment for curve 4, deflected 90°. In this point, then, angle of incidence of magnet is F C G=30°, and angle of obliquity of polar force z C F=90°. Let now the whole magnetic polar force=M, and the whole force of magnet=m, then, because the needle is at rest, either the whole or some part of the magnetic polar force must be in equilibrio with the whole or some part of the force of the magnet; and as these forces will depend upon the angle of obliquity, we have for points d and r, calling the function we require=f, the following equations:—

$M \times f\,30° = m \times f\,15°$, and $M : m :: f\,15° : f\,30°$ for point d,

$M \times f\,90° = m \times f\,30°$, and $M : m :: f\,30° : f\,90°$ for point r.*

But between these four functions, in the proportions thus deduced, we obtain $f\,15° : f\,30° :: f\,30° : f\,90°$.

Now this proportion leads at once to the value or nature of the function required=f, since in the ordinary trigonometrical calculations and tables we find that the sines of these angles fulfil the conditions of this proportion. In fact, we have sin $14\frac{1}{2}$: sin 30° :: sin 30° : sin 90°, that is,

* The student will easily see, that to represent the equilibrium of the forces in operation, we must multiply the total magnetic force by the function of the angle of obliquity at which the force acts, and upon which the modification of the whole force depends. Thus, suppose that when the obliquity of action was a given quantity, that only $\frac{1}{8}$th part of the total force, for example, was effective in retaining the needle at a given deflection, we should, in this case, express it by $\frac{1}{8}$ of M, calling generally the magnetism M; that is to say, we should multiply M by $\frac{1}{8}$. But since we do not know what portion of the total forces are in operation, we are content to represent it by some function of the angle of obliquity; and, therefore, in the above, write $M \times f\,30°$, or $m \times f\,15°$, as the case may be. It is further evident that, in the equilibrium of these forces, we have in all cases some portion of the total polar force acting at a constant distance in equilibrio, with some portion of the total force of the magnet acting at variable distances from the needle; hence we write, in the cases quoted,

$$M \times f\,30° = m \times f\,15° \text{ and } M \times f\,90° = m \times f\,30°.$$

$\cdot 250 : \cdot 5 :: \cdot 5 : 1$,* which is sufficiently near for our purpose, and leaves little or no doubt as to the nature of f.

197. From this investigation, then, we may conclude that the action of magnetism on a magnetic needle, considered as a lever, is proportionate to the sine of the angle of obliquity of its direction; and that hence the effective force which operates in restoring the needle to its meridian, when drawn aside from it, is directly as the sine of the angle of its deflection—an important deduction. "If," says Robison, "M. Lambert's discoveries had terminated here, it must be granted that he had made a notable discovery in Magnetism."

This important result was fully established by a variety of other experiments. Thus taking other points, f and g, equally distant from centre C, or very nearly so, we have the angles of incidence g C $a = 30°$, and f C D $= 75°$; the needle for curve 1 being deflected 15° in direction C a; and for curve 2 being 30° in direction C D. The obliquities of the respective polar forces are consequently z C $t = 15°$, and z C $y = 30°$.

From whence we obtain for points g and f the two following proportions:—

$$m \times f^{n}\, 30° = \text{M} \times f^{n}\, 15°, \text{ which gives } m : \text{M} :: f^{n}\, 15° : f^{n}\, 30°;$$

and

$$m \times f^{n}\, 75° = \text{M} \times f^{n}\, 30°, \text{ which gives } m : \text{M} :: f^{n}\, 30° : f^{n}\, 75°.$$

From these four functions we have, by the ordinary rules,

$$f_{n}\, 15° : f_{n}\, 30° :: f^{n}\, 30° : f_{n}\, 75°;$$

that is, sin 15°: sin 30°:: sin 30°: sin 75 (196);

or, $\cdot 2589 : \cdot 5 :: \cdot 5 : \cdot 966$.

And $\cdot 2589 \times \cdot 966 = \cdot 5 \times \cdot 5$, or $\cdot 250 = \cdot 258$, which is a sufficiently close approximation.

198. Having thus determined the first, and apparently the most simple law of Magnetism, Lambert proceeds to apply it in his further investigations of the law of force as regards distance. With this view, let the total polar force, which draws the needle to its meridian, be considered as unity or 1, and suppose that the magnet E being in some

* See (182) note.

point of the curve D E G, the needle is deflected 30°, and is in the direction C D. In this case the sine of 30° being ·5, the effective polar force becomes represented by $1 \times \cdot 5$ (196, note); that is to say, it may be expressed by ·5. Now the needle being stationary, in whatever point of curve 2 the magnet be placed, it is clear that the oblique or effective force of the magnet in any point, *d*, E, *e*, must be equal also ·5; because in these points it exactly balances the polar force.

Now, let the actual or inherent force of the magnet at any distance, C E, C G, &c. $= m$, and call the angle of incidence or obliquity of its action $= \phi$, then we have the effective force in every point of the curve $= m \times \sin \phi$; but as this force, as just shown, must be $= \cdot 5$, we have therefore by these two values

$$m \times \sin\phi = \cdot 5 \text{ and } m = \frac{\cdot 5}{\sin \phi}.$$

Taking now the different angles of incidence, *d* C D, E C D, *e* C D, &c., for the successive points *d* E, *e*, &c., and which are by construction, 15, 30, 45, 60, &c., up to 120° (192), and dividing ·5 by the sines of these angles, we obtain the value of *m*, or absolute force of the magnet, in each point of the curve at a measurable distance from the centre C; consequently, in laying off the respective distances C D, C *d*, C E, &c., upon a given scale, we have the respective values of the force and distance represented by numbers. M. Lambert estimates the distance in terms of a unit of measure = ½ the length of the needle. The forces and distances thus determined will be as in the following table:*—

Points of curve ..	*d*	E	*e*	F	*f*	G
Distances = *d*	2·71	3·62	4·17	4·33	4·48	4·61
Forces = *f*	1·93	1·00	0·7	0·57	0·51	0·5

199. It will be observed, that in comparing these distances

* This way of noting the results of the experiment is not the same as that adopted by M. Lambert, who gives several distinct and elaborate tables, which, in a rudimentary work of this kind, could not well be introduced. It became requisite, therefore, to simplify them, and bring the results under a less complicated form. No alteration, however, has been made in the course followed by the author, or in his numbers, which are given as found in his table.

and forces as before (182), there is a general approximation to the law of the inverse square of the distance, more especially in the points F, *f*, G, in which the products of the forces, multiplied by the squares of the respective distances (177), are 10·6, 10·2, 10·6; the nearer points, however, as *d* E *e*, give the products 13·87, 13·10, 12·1, which exhibit greater differences. M. Lambert, however, goes on to observe,—that the distances here given are taken between the extremity of the magnet E, and centre, C, of the needle,—that these may not be the true distances of the magnetic action,—still he prefers letting the numbers remain as they are in the table, and subject them to such calculation as may be found requisite, merely bearing in mind, that whatever be the true distances, they must be in some inverse ratio of the forces.

200. Supposing Magnetism to be a species of central force, analogous with the force of gravity (179), it would then come under the same general law as regards the distance of its action, and would be in the inverse duplicate ratio of the distance (175). Assuming this to be the case, we may obtain the true distances corresponding to the forces by means of the general expression for this law. Thus, let $f =$ the effective force of the magnet in points *d* E, *e* F, &c., and let the true distance of action we require to find $= \Delta$, then we have

$$f \,\alpha\, \frac{1}{\Delta^2}, \text{ and, consequently, } \Delta \,\alpha\, \frac{1}{\sqrt{f}}$$

If, therefore, we extract the roots of the numbers in the preceding table, represented by *f*, we shall, in carrying out the operation indicated in the above formula, obtain a series of numbers which, although not equal to the true distances, will still vary in the same direct ratio, and which may become equal to the true distances if multiplied by some constant $=$ C, so that, in representing these numbers by δ we should have $\Delta = \delta \times$ C.*

* The student must remember, that although a given quantity may

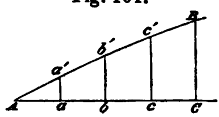
Subjecting, then, the forces f to the indicated operation $\frac{1}{\sqrt{f}}$, we obtain, for the respective points d, E, e, F, &c., the following proportionate distances :—

Points	d	E	e	F	f	G
Proportionate distances $=\delta$ ..	0·719	1·00	1·189	1·316	1·39	1·414

M. Lambert deduces for the mean value of the constant, by which these numbers must be multiplied, $c = 2{\cdot}2$, as given from the whole series of experiments in the successive curves 1, 2, 3, 4, 5 (Fig. 103). The true distance, therefore, will be represented by $\Delta = \delta \times 2{\cdot}2$; so that by comparing the product of the above numbers by 2·2 with the measured distances $= d$, as given in the preceding table, we immediately arrive at the required correction, if any.* Take, for example,

change in the same proportion as another and greater quantity, yet we cannot ever consider the two quantities as equal. To complete the equality it becomes requisite to multiply the lesser quantity by some constant number. Take, for example, the right-angled triangle A C B, and suppose it divided by parallels $a\,a'$, $b\,b'$, $c\,c'$, &c.; and in such way, for example, that distance A a from the vertex A is twice the length of the parallel $a\,a'$. Then we have A b double of $b\,b'$, and A c double of $c'\,c$, and so on; and $a\,a'$, $b\,b'$, $d\,d'$, &c., will increase in exactly the same proportion as A a, A b, A c, &c.; so that if A $b = 2$ A a, then $b\,b' = 2\,a\,a'$, and so on. Still $a\,a'$, $b\,b'$, &c., can never be taken equal to A a, A b, &c. We may, however, in this case make them equal by multiplying $a\,a'$, $b\,b'$, &c., by 2, which is the constant quantity here required, but which constant in the above formula we require to determine.

Fig. 104.



* To get the value of C, let the difference between the true and observed distance $= x$, then we have $d \pm x = \delta \times$ C. Take now any two values of d, say in points E and G, as given in the former table, then we have

$$3{\cdot}62 \pm x = 1 \times \text{C for point E},$$

$$\text{and } 4{\cdot}62 \pm x = 1{\cdot}414 \times \text{C for point G}.$$

Subtracting equation of point E from equation for point G, we have

$$1{\cdot}01 = {\cdot}414 \times \text{C and C} = \frac{1{\cdot}01}{{\cdot}414} = 2{\cdot}4 \text{ nearly}.$$

the numbers in the preceding table at points d and G, then we have for Δ, that is, the true distance,

$$0{\cdot}719 \times 2{\cdot}2 = 1{\cdot}58 \text{ for point } d,$$
$$\text{and } 1{\cdot}414 \times 2{\cdot}2 = 3{\cdot}11 \text{ for point G.}$$

But the measured distances for these points $= d$, as given in the former table are $d = 2{\cdot}71$ for point d,

$$\text{and } d = 4{\cdot}61 \text{ for point G.}$$

The respective errors, therefore, or

$$d - \Delta \text{ are } 2{\cdot}71 - 1{\cdot}58 = 1{\cdot}13 \text{ for point } d,$$
$$\text{and } 4{\cdot}61 - 3{\cdot}11 = 1{\cdot}5 \text{ for point G.}$$

The mean of these, or $\frac{1{\cdot}13 + 1{\cdot}5}{2} = 1{\cdot}31$ nearly, which turns out to be the mean value of x upon the whole series of experiments in the different curves, that is the quantity to be subtracted from the measured distances in order to obtain the true distances, upon the hypothesis that the force is as the squares of the distances inversely, as in the case of gravity. These numbers x and C being determined, we have $d - 1{\cdot}31 = \delta \times 2{\cdot}2$, and hence $d = \delta \times 2{\cdot}2 + 1{\cdot}31$, which is the formula deduced by M. Lambert for determining d by calculation, and comparing the result with d as given in the first table.

In extending this formula through the numbers for the series of curves 1, 2, 3, 4, 5, deduced as in the first table (198), M. Lambert finds the differences between the measured and calculated values of d comparatively small, and as often positive as negative; and hence concludes that the formula $d = \delta \times 2{\cdot}2 + 1{\cdot}31$ is, upon the whole, correct.

201. Admitting the truth of this formula, we arrive at a somewhat remarkable result: viz., that to obtain the distance, the square of which is in a reciprocal inverse ratio of the force of the magnet, we must take, for the true distance,

Upon a mean of the whole series of experiments for all the curves, 1, 2, 3, 4, 5, Mr. Lambert finds the mean value of $\text{C} = 2{\cdot}2$, or, as he expresses it, $\frac{11}{5}$.

the distance been the centre of the needle and the extremity of the magnet, minus the quantity 1·31, which is greater than half the length of the needle.* So that what may be called the centre of attraction of the magnet is found out of the magnet, and what may be called the centre of attraction of the needle is found out of the needle. So that the common centre of attraction may be conceived to be in the semicircular interval A *p* (Fig. 103) being as much nearer the needle *p q*, as its force is less than that of the magnet E. M. Lambert thinks that, in the case before us, it falls about the point *r*, at 1·31 distance from the centre of the needle C A, being the least radius or distance at which the magnet could be placed without altogether fixing the needle independently of the polar force.

Professor Robison appears to view this deduction as somewhat anomalous, and as arising out of the complicated nature of the experiment. Yet if the force be such as anticipated by Lambert, there does not appear any greater difficulty in conceiving such a result, than in conceiving the common centre of gravity of two bodies of unequal magnitudes to fall without the bodies. Thus the common centre of gravity of the earth and moon is neither within the earth or moon, but in some point intermediate between them; being as much nearer the earth as the mass of the earth is greater than that of the moon.

Under this impression, however, the professor was led to repeat Lambert's experiments with magnets, consisting of a slender steel rod, terminating in small balls, in which case he found the force to be nearly in the centre of each ball, and to vary in the inverse duplicate ratio of the distances with singular precision.

202. Such are the principal features of Lambert's first memoir on the important question of the law of magnetic force. In a following subsequent memoir "On the Curvature of the Magnetic Current," he continues his series of

* The unit of measure being made = half the length of the needle (198).

experiments, and examines with singular ingenuity, mathematical skill, and address, the action of the directive or polar force of a magnet upon a small needle. In the preceding experiments Lambert had always preserved the axis of the magnet in a right line passing through the centre of the needle. This condition, however, is not altogether requisite in every case. He therefore, in these subsequent researches, places the magnet more or less oblique to that line, but always preserving the same angle of obliquity for comparative experiments. The question whether such curves as those which are represented in Part I. (28), depend on a circulating fluid, Lambert considers of no moment. Still the curves exist, and the problem for determining the nature of such curves will still arise, the axis of a small needle freely suspended will, in various points, always be a tangent to these curves ; so that we may, without ambiguity of language, call them "curves of the magnetic current." If there be such a current, the term will be true to the letter; if not, the algebraic nature of such curves will suffer no change. In order to determine the nature of these curves, as bearing on a large and important class of natural magnetic phenomena, Lambert endeavours to examine still further the general laws of Magnetism, and the position, size, figure, and force of the great magnet which he supposes to reside in the earth. The limits of this work will not permit us to enter fully upon this beautiful memoir, which, as remarked by Dr. Robison, would have done credit to Newton himself; more especially as it embraces other considerations than those immediately connected with our present subject. So far, however, as it bears on the elementary laws of Magnetism, Lambert concludes, "that the effect of each particle of the magnet on each particle of the needle, and reciprocally, is as the absolute force or magnetic intensity of the particles directly, and as the squares of the distances inversely."

203. About twenty years after Lambert's experiments, Coulombe turned the attention of his ingenious and compre-

hensive mind to this subject;* and by means of the torsion balance (132), and method of oscillation (138), not only confirmed the deductions of Lambert, but also added to our knowledge of magnetic force in a most extraordinary degree. Having placed a linear magnet, 24 inches in length, in the stirrup of his balance (132), he was enabled to measure the force required to maintain this needle at various angles from its natural direction, and thus, by a direct experiment, he confirmed the principle of Lambert (197), viz., that the force urging a magnetic needle toward the magnetic meridian when drawn aside from it, is proportional to the sine of the angle of its deflection. Referring to the explanations given (133), the following are the forces and angles in four different experiments, and by which it will be seen that the forces or degrees of torsion requisite to maintain the needle at the given angles, are sensibly proportional to the sines of these angles.

Micromatic circles	1	2	4	5·5
Degrees of torsion	349·5	698·75	1394	1895
Angles of Deflection ..	10°-30	21°-15	46°	85°
Sines of angles	·1822	·3624	·7193	·9961

204. To understand clearly these results, it will be necessary to recollect, that the reactive force exerted by the wire when subjected to twist, is exactly proportional to the degree of twist to which it has been subjected. This is the fundamental principle of the instrument (132).† This degree of twist or torsion may be either measured by actually twisting the wire itself at its upper extremity, Fig. 80 (132), against a resisting force beneath, or otherwise turning the wire from below against a fixed point above. In either case the torsion force is proportional to the angle of torsion. Now, in such experiments as those just quoted, in which a magnetic needle

* Memoir of the Royal Academy of Sciences, 1786 and 1787.

† We avail ourselves of this opportunity of correcting an error, seventh line from the top, p. 119, Parts I. and II., for "sine of the angle or arc," *read* angle or arc.

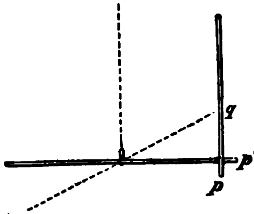
is forced from its directive position through a given angle, say 46°, by actually twisting the wire any number of degrees against the directive force of the needle, and by which it tends to the magnetic meridian, we must, to obtain the actual force of torsion, holding the needle at any given angle, subtract from the number of degrees which we have twisted the wire, the degrees representing the angle of deflection of needle; for, imagine that we had forcibly retained the needle in its original position, whilst we had twisted the wire 4 circles of the micrometer (Fig. 80, sec. 132), that is 4 times 360= 1440°, and that, on liberating the needle, it became deflected, and rested at 46°, then, as is evident, the total torsion of the wire would become relaxed by that quantity, and we should have for the absolute force of torsion, holding the needle at 46°, 1440−46=1394°, as given in the table; and similarly for the other given angles.

205. Having determined this point, Coulombe proceeds to examine the law of the repulsive force of two similar magnetic poles, and in the following way:—

Two equally-tempered and magnetic steel wires, each 24 inches in length, and about the $\frac{1}{10}$ of an inch in diameter, were placed, one of them in the balance, and the value of its directive power or force dragging it to the meridian, at any given angle determined. This force, in terms of the torsion force, was, for this particular case, equal to 35°, for 1° of deflection of the needle; that is to say, in order to force the needle 1° from its meridian, it was requisite to turn the mecrometer, Fig. 80 (133) 35° of the circle.* This being ascertained, the other wire was placed vertically in the me-

* Coulombe found that 2 circles of torsion deflected the needle 20°, which gave a force of torsion for 20°=720−20=700. Now the directive force of the needle being as the sine of the angle of deflection, we may, from this experiment, obtain the force for any other angle m, since we have this proportion, 700 or force at 20° : f, the force at angle m :: sin 20 : sin m, or $f \times \sin 20 = 700 \times \sin m$, or $f = \frac{700 \times \sin m}{\sin 20}$. If we

Fig. 105.



ridian, with its inferior pole at right angles to the similar pole of the needle, as represented in the annexed Fig. 105, and in such way as to admit of the two wires being considered as intersecting each other at an inch within their similar polar extremities, $p\ p'$. As a necessary consequence (31), the pole p' of the horizontal needle, placed in the balance, becomes repelled, and turns away from the pole p of the fixed vertical needle, until arrested by the torsion of the wire, and a balance obtained to the repulsive force. In this case the needle was balanced at an angle of torsion of 24°. The next step was to determine what amount of torsion was requisite to balance the repulsive force at certain other angles or distances between the repelling poles, $p\ p'$. With this view the wire was twisted against the repulsive force by turning the micrometer 3 complete circles, or $3 \times 360° = 1080°$. The pole p' of the needle now stood within 17° of the vertical pole p. In like manner, 8 circles or $8 \times 360° = 2880°$, brought the repellant poles within 12° of each other. Let us pause here for a moment to consider what are the actual or total forces in operation at each of the arcs of distance, 24°, 17°, and 12°.

206. In the first place, we have to consider, that not only is the horizontal needle, p', pressed back toward the vertical needle, p, by the reactive force of the torsion, but it is likewise urged toward the vertical needle by its own directive power or tendency to the meridian; we must therefore add this assistant force in each case. This is effected by turning it into degrees of torsion, at the rate of 35° of torsion for

take the arcs themselves, instead of the sines, which we may do here without any great error, we have $\frac{f = 700\ m}{20} = 35\ m$. If we take $m = 1°$, then the force equals 35°, that is 35° of torsion, as observed.

each degree of angular deflection from the meridian, according to the preliminary experiment above given (204); for, since as a fundamental principle of the instrument, the torsion force goes on regularly increasing with the angular twist of the wire, it is sufficient to know the actual force for one degree, to get the force for any number of degrees In the first experiment, therefore, when the angular distance of the poles pp' was 24°, the total force in terms of torsion, balancing the repulsive force, must have been $24 + (24 \times 35) = 24 + 840 = 864$. For force at angular distance, 17°, we have to combine the new torsion = 3 circles, with the torsion for 17°, and the directive force at 17°, so that we have $(3 \times 360) + 17 + (17 \times 35) = 1080 + 17 + 595 = 1692$ for the total force at angle 17°. In like manner, we obtain the total force at $12° = 8$ circles $+ 12 + (12 \times 35) = 2880 + 82 + 420 = 3312$; so that the distances and corresponding forces will stand thus:—

Distances	12	17	24
Forces	3312	1692	864

207. Now, these forces are in the inverse duplicate ratio of the distances, or very nearly. Thus, at distances 12 and 24, which are as 1 : 2, we have the inverse forces 864 and 3312, which are as 1 : 4; that is to say (174), we have the inverse proportion $3312 : 864 :: 2^2 : 1$ or $4 \times 864 = 3312$, nearly, or $3456 = 3312$. Had the force at 24° been 868 instead of 864, the accordance would have been complete. Now the difference 36 between these numbers is not above one degree of error in the position of the needle, at the rate of 35° of torsion to 1° of angular deflection; the result, therefore, is perhaps as near as could be expected, for it is to be remembered that the action of the poles upon each other is a little oblique; the distances are really as the chords of the arcs, and not as the arcs themselves, beside that the experiment is not an experiment with two particles, but two portions of a magnetic wire. Admitting all this, however, it is still to

be observed, that the force at the near distance, 12, is not so great as it should be by calculation in the proportion of 3312 : 3456, taking the force at 24 as 864; we shall have occasion to refer to this fact as we proceed.

208. These experiments, by Lambert and Coulombe, were followed up, about the year 1817, by Professor Hanstein, of Christiana, who, in a valuable work entitled "Inquiries concerning the Magnetism of the Earth," deduces many important laws of ordinary magnetic forces.

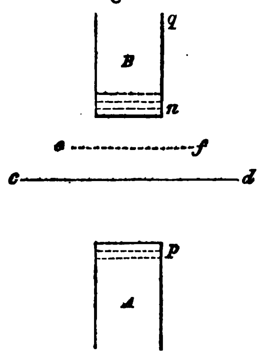
Although Professor Hanstein's method of experiment is virtually the same as that of Hawsksbee (182), yet the method of analysis is peculiarly his own. Hanstein's apparatus may be taken as identical with that described (134) Fig. 82, the straight line, E W, being divided into portions such that ten of them were equal to the half axis of the artificial magnet used in the experiment. Having assumed that the magnetic intensity of any particle in a magnet is proportionate to some power of the distance from the magnetic centre (26); and that the force between any two particles is in some inverse ratio of their mutual distance, a general expression is deduced, for the effect which a linear magnet would have upon a magnetic particle, situated anywhere in the line of the prolonged axis of the magnet. This determined, and the angles of deviation of the needle (Fig. 82), at different distances from the magnet M, accurately noted for each distance, the Professor proceeds to compare the results of calculation with those of the actual experiment, and shows that the supposition of the force being in an inverse power of the distance equal to 1 or 3, entirely disagrees with observation; whilst, on the other hand, if the power be made equal to 2, the numbers found by experiment differ but little from those found by calculation. The value of the power of the distance, representing the increase or decrease of intensity from the magnetic centre, does not appear to have so great an influence on the result. Hanstein, however, thinks that this power is also equal to 2, although, by taking it as

1 or 3, the differences from actual observation are not always considerable.

From these inquiries, Hanstein thinks he is entitled to conclude, "That the attractive or repulsive force with which two magnetic particles affect each other, is always as their intensities directly, and as the square of their mutual distance inversely," thus confirming the deductions of Lambert and Coulombe.

209. *Further Inquiries concerning the Nature and Laws of Magnetic Forces.*—Although our knowledge of magnetic force has been very greatly advanced by these several researches, it yet remains to be seen whether the law deduced be a general law, applicable to every case of magnetic action considered as a central force (179), or whether it be only a particular law of some peculiar agency operating between the surfaces of magnetic bodies in a way similar to that of electricity, which, as now well known, is confined to the limiting surfaces of opposed conductors.*

Fig. 106.



We have seen (33) that when a magnetic bar A, Fig. 106, is opposed to a similar, but smaller, bar of iron B, then a new polarity *n* is induced in the near parts *n* of the iron, opposite in kind to that of the opposed polarity A, whilst another polarity, *q*, arises in its more distant parts, similar in polarity to that of the polarity A, but opposite to that of the induced polarity *n*: this, however, is not all. On further examination, we find (37) that the temporary polarity *n*, thus induced in the near surface of the iron, operates in its turn on the near surface *p* of the magnet, producing there, by a species of reflection or rever-

* Rudimentary Electricity, (21), p. 17, and (98), p. 111, second edition.

beration, what may be considered as a new polarity *p*, opposite in kind to that of the induced polarity *n*, but similar to that of the permanent polarity A; that is to say, a portion of the force, which under the ordinary conditions of magnetized steel is directed towards the centre of the magnet (28), becomes now determined toward the iron in direction *p n*.

These changes induced in the magnetism of the two bodies, have been considered by some writers as casual and disturbing forces, superadded as it were to the primary magnetic action, which they imagine to be a distinct power, or emanation as it were from a centre, and operating in the way of other central forces (179). Michell had evidently adopted this view (190); as also Dr. Robison, who thinks that the phenomena of magnetic attraction and repulsion, as commonly observed, are not calculated to develop the real law of magnetic force: "For in the experiments made on attraction at different distances, the magnetism is continually increasing, and hence the attraction will appear to increase in a higher rate than the just one;" and that, hence, "the observed law must be different from the real law." * If we look, however, very narrowly into the nature of this kind of physical force, we shall immediately perceive that it is altogether an inductive process. Induction, as observed by Faraday, in respect of electricity,† is the essential function of all magnetic development. So far, therefore, from these induced actions being merely superadded or disturbing forces, they are the very essence of the force itself. It is in fact the mutual play of these inductive powers which constitutes magnetic action in all its variety of form; we recognize no other action in the observed phenomena of magnetic attractions and repulsions: and it is hence to the laws of these induced changes to which we must look for an intelligible development of what we have termed the general law of magnetic force.

* Mechanical Philosophy, vol. iv. pp. 217 and 273.

† Researches in Electricity, 1178.

210. It is here to be remembered that we know nothing of that peculiar condition of steel we term magnetic, except through the medium of its effects upon ferruginous bodies. We may, however, infer, as already explained (14), that in a magnetized bar two forces are developed, the tendency of which is to recombine and restore the condition of neutrality under which they previously existed. Taking, therefore, a magnetic bar apart from the influence of all other ferruginous matter, we may consider the action of these opposite forces as being directly upon or toward each other, either through the particles of the steel, or through surrounding space. The experiment we have adduced (28), Fig. 16, is highly illustrative of this kind of action: the ferruginous particles being evidently bent into curves, and apparently uniting the forces in points similarly placed, on each side of the magnetic centre. When, therefore, we present to one extremity *p*, Fig. 106, of a magnet A, a mass of iron B, capable of assuming the magnetic state, or otherwise, the opposite pole of another magnet, we divert, as it were, some portion of the force, resident in that extremity *p*, from its previous direction towards the centre of the bar A, and cause it to act in the direction of the opposed iron or other opposed polarity, as appears strongly indicated in Fig. 17 (28). And this it is which constitutes the reciprocal or reflected force *p*, Fig. 106, to which we have just adverted; and it is upon these two forces that the reciprocal force between the two bodies depends.

211. This species of reverberation of force between the opposed poles having once commenced, may still continue; that is to say, a secondary wave or reverberation may proceed from the new force *p*, which again reaching the iron, is again reflected back upon the magnetic pole, calling into activity a still further portion of the opposite force in the direction of the iron; each reverberation becoming weaker until the wave vanishes, as it were, into rest.

The late Mr. Murphy, of Caius College, Cambridge, ap-

plies, in his profound mathematical work on Electricity and Heat, a somewhat similar principle to the theory of electrical action, and which he terms, "Principle of Successive Influences." Professor W. Thomson also, of the Glasgow University, resorts to a view of this kind, conceiving that in the reciprocal force of attraction, as exerted between a charged and neutral body, certain images or reflections of power are produced within the opposed conductors, and which become perpetuated in a way similar to that of reflections between two mirrors.*

How, or in what way, the kind of influence to which we have just adverted (209) commences, or from whence it first proceeds, has never yet been fully explained. The first action may, for anything we know to the contrary, proceed from the influence of the iron on the magnet; the magnet being a body in a peculiar condition, which renders it sensible of impressions from ferruginous matter. Hence may arise that determination of a given portion of the polarity next the iron which we have just described (210), and upon which may depend a subsequent and similar determination of the opposite polarity resident in the iron toward the magnet, and a retiring, as it were, of the similar polarity in the reverse direction. In whatever way, however, these two inductions arise, they are evidently the immediate source of the reciprocal attraction as observed to arise between the opposed bodies: this appears in great measure evident in Fig. 17 (28). On the contrary, when these inductive actions do not arise, or if they be resisted by any existing magnetic condition, then not only is there an absence of all apparent force, as we perceive in presenting to the pole of a magnet any non-magnetic body (30), but a totally opposite force ensues; the bodies actually repulse each other; as also fully indicated in Fig. 18 (28). Moreover, it may be shown, that the attractive force between a magnetic pole and soft iron, is only in proportion to the induction of which the iron is

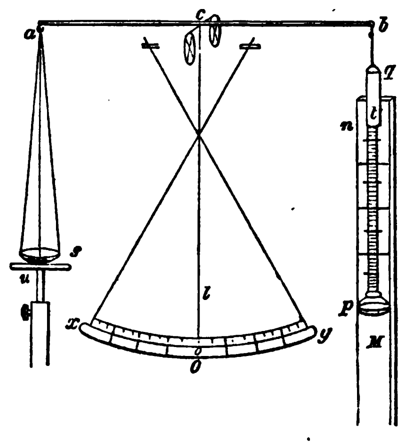
* Rudimentary Electricity, (101), p. 115, second edition.

susceptible, whatever the amount of permanent magnetic development in the steel.

Magnetic attractions and repulsions then, as commonly observed, being the result of a species of inductive reverberation (209) between opposed magnetic bodies, it follows: that in order to arrive at a correct view of this species of force, and determine the law of its action, we must necessarily commence with an investigation of the laws and operation of the elementary forces of induction.

212. The magnetometer already described (126), Fig. 76, and the simple balance-beam adverted to (37), Fig. 29, are well adapted to the measurement of these and other magnetic forces. The first has been very fully explained in all its details (126); the latter when applied to very refined purposes should be mounted on friction-rollers, such as shown Fig. 75 (126), and the whole of the framework, with its attached arc, be sustained on a central sliding column of support, the altitude of which can be varied by means of rack-work, as in the column of the magnetometer, Fig. 76, so as to change the distance readily between the small trial cylinder *t*, Fig. 107, or other body suspended from one of the arms, and any other magnetic substance M brought to act on it. The general arrangement is represented in the annexed figure, the framework and column of support being omitted, in order to avoid complication. In the instrument as here shown, the suspended

Fig. 107.



bodies play freely on two pins, run transversely at *a* and *b*, through slits cut in the extremities of the beam, which is 16 inches long. The scale-pan *s* is supported on a small circular plane, set on a sliding-piece *u*, so as to admit of adjustment. The arc *x o y* is the ⅛th part of a circle, and is divided into 100 parts on each side the centre *o*, which is marked zero; the radius of the arc is 16 inches, the index *l* is neatly formed of three or four pieces of reed straw, terminating in a fine bristle; it is attached to the balance at *c* by insertion on a brass pin projecting from a light brass band encircling the beam, and through which the axis passes. The forces corresponding to any given number of degrees of the arc, are determined experimentally by placing small weights, either in the scale-pan at *s*, or on the suspended iron *t*. The axis being a little above the centre of gravity of the beam, the balance does not immediately overset, but admits of a given inclination: the forces in this case will be very nearly as the small angles at which the beam inclines; so that the degrees of the arc measuring these angles will be nearly as the weights inclining the beam. Attractive forces are measured on the arc in direction *o x*, repulsive forces in the opposite direction *o y*.

This balance is only applicable to the measurement of very small forces, such as those exerted by magnets and iron at distances approaching the limit of action. In the application of it, we employ precisely the same kind of apparatus for sustaining the magnets and iron as that already described for the Hydrostatic Balance (126).

213. The direct and reciprocal forces of induction (209) are examined by these instruments according to the methods described (128, 129, 130). To determine the law of the direct induction (33), the magnet and iron are attached to a divided scale, Fig. 79, and then brought under the trial cylinder; so that in making the distance *a b* constant, and varying the distance N S, the rate of increase or decrease of the induction upon the near extremity S of the inter-

mediate iron, as measured by the distant and associated polarity at *b*, may be pretty fairly estimated; the reciprocal attraction between the trial cylinder *a*, and the induced pole *b*, will, as observed by Newton (181), entirely result from the intermediate iron; hence we may infer, all other things being the same, that the proximate induction at s will vary with the distant polarity at *b*. When the bodies are laid horizontally, as in the annexed Fig. 108, the trial cylinder *t* is immediately over the distant extremity of the iron, the force being taken through a short cylindrical armature *a*. Fig. 78 (129) is further illustrative of this experiment. To measure the reflected force (37), we first observe the degrees of attraction between the pole of a magnet and the trial cylinder *t*, either placed vertically, as in Fig. 107, or horizontally, as in the annexed Fig. 109. A mass of iron *m*, or the opposite pole of a permanent magnet, is then caused to approach the pole *p* of the magnet M, through certain measured distances as before: this will cause the index to decline (37). Now the degrees of declination may, within certain limits, be taken as a measure of the reciprocal force of the induced pole *n* upon the pole *p* of the magnet M, the distance of the trial cylinder *t* being constant, and the force allowed to operate through a short cylindrical armature of soft iron as before.

Fig. 108.

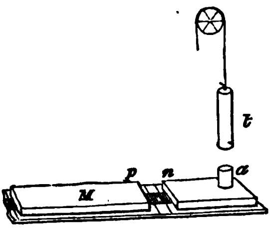
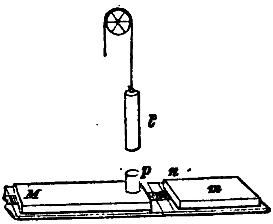


Fig. 109.



The forces of induction may in all these cases be considered as proportional to the square roots of the degrees of attraction, as given by the instrument, since by a law of

charge which has been fully established in similar electrical actions,* and which we shall further show as equally true for magnetic actions, the force is as the square of the quantity of magnetism in operation (229).

214. It appears by an extensive series of experiments conducted in this way, that a limit exists in respect of these elementary inductive forces, different for different magnets, and varying with the magnetic conditions of the experiment, toward which the increments in the force continually approach with greater or less rapidity, as the distance *p n*, Fig. 107, is diminished, as if the opposed bodies were only susceptible of a given amount of magnetic change.

Taking the force toward the limit of the action, the amount of induction is in some inverse ratio greater than that of the simple distance; it was not found, however, in any case which could be satisfactorily determined, to exceed the inverse sesquiplicate ratio, or $\frac{3}{2}$ power of the distance (176). As the distance becomes diminished, the induction approaches the inverse simple ratio of the distance (175), and varies commonly according to that law. At less distances, the induction begins to vary in some ratio less than that of the simple distance inversely, such, for example, as the $\frac{2}{3}$ power of the distance inversely (176). At small distances the induction was generally observed to be as the $\frac{1}{2}$ power or square roots of the distances inversely (175); thus causing corresponding changes in the general law of attraction reciprocally exerted between the opposed bodies.

When the convergence is slow, the law of the induced forces may be taken for a long series of terms as constant; but should any circumstance interfere to accelerate the convergence, such as a particular texture or condition of the magnetic steel or iron, or a high magnetic power, then the law of force may appear subject to irregularity. As a general result, however, we may conclude, that the elementary force

* Rudimentary Electricity, (102), p. 117, second edition.

of magnetic induction is as the magnetism directly, and from the $\frac{1}{2}$ to the $\frac{3}{2}$ power of the distance inversely.

215. This understood, let us see how far these results may be applied in explanation of the different laws of force experimentally deduced by the many eminent philosophers who have turned their attention to this important question.

Let A, Fig. 106 (209), represent a magnet opposed to a similar mass of iron B, at some given distance $p\,n$. Let the small space n be taken to represent the direct induction on the near extremity of the iron B, and the small space p, the reciprocal or reflected induction on the near pole of the magnet A; and suppose that every magnetic particle in n attracts every magnetic particle in p, and reciprocally. Moreover, let all the particles in $n = a$, and all the particles in $p = b$, and take distance $p\,n$ as a unit of distance, then total force at this distance $= 1$ will be represented by $a \times b = a\,b$. For the attraction of one particle of n to all the particles in p will be as b; the attraction of two particles of n to all the particles of p will be as $2\,b$; of three particles, as $3\,b$; of m particles, as $m\,b$; so that if b represent all the particles and $m = a$, the total force will be $= a\,b$.

Suppose, now, we decrease the distance. Let the distance, for example, be reduced to one half $p\,n$, the magnet A being brought up to the line $c\,d$, then supposing the induction to vary as the simple distance inversely (214), n will become $2\,n$, and p will become $2\,p$. In this case call the particles in $n = 2\,a$, and the particles in $p = 2\,b$; then, considering $2\,a$ and $2\,b$ as double particles, we have attraction of one double particle in n for all the double particles in p, as $2\,b$; of two double particles in n, for all the double particles in p, as $2 \times 2\,b = 4\,b$; of three double particles, as $3 \times 3\,b = 9\,b$; and so on to m particles, which will be as $m \times 2\,b = 2\,m\,b$. If $m = 2\,a$, the total force will be represented by $2\,a \times 2\,b = 4\,a\,b = 2^2 a\,b$.

Let distance $p\,n$ be now further reduced. Suppose it

reduced to $\frac{1}{3}$ *p n*, and that the magnet be now brought up to the line *e f*. Then, according to the same law of induction, *n* becomes 3 *n*, and reflected force *p* becomes 3 *p*. Reasoning as before, we have total force $= 3\,a \times 3\,b = 9\,a\,b = 3^2\,a\,b$. If distance be now diminished to $\frac{1}{4}$ *p n*, we have similarly total force represented by $4\,a \times 4\,b = 16\,a\,b = 4^2\,a\,b$, and so on.

Taking, therefore, first force *a b* as a unit of force, and distance *p n* as a unit of distance, we have, at distances 1, $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, &c., the corresponding forces 1, 2^2, 3^2, 4^2, &c.; that is to say, the forces are in the inverse duplicate ratio of the distances (175), according to the law of Lambert and Coulombe.

Exp. 53. This law may be verified experimentally by placing a magnet, Fig. 107 (212), immediately under the trial cylinder *t*, and taking the forces within a range of about $\frac{1}{4}$ to $\frac{3}{4}$ of the sensible limit of action. Thus the forces and distances, as deduced by the hydrostatic magnetometer (126), were as follow; the distances being taken in tenths of an inch, the forces in degrees—

Distances	12	10	8	6	5
Forces	2	3	5	8·5	12

216. We will now take a case in which the induced forces, in approaching a limit (214), are no longer in the inverse ratio of the simple distances, but as the $\frac{1}{2}$ power or square roots of the distances inversely. Then, taking a unit of force $= a\,b$, and a unit of distance $= p\,n$, and reasoning as before, suppose in decreasing the distance to line *c d*, that is, to $\frac{1}{2}$ the former distance, induced force *n*, instead of becoming 2 *n*, is now only 1·4 *n*, or nearly, whilst *p*, instead of becoming 2 *p*, is now only 1·4 *p*, that is, the square roots of the distances inversely. In this case, calling force at distance unity $= a\,b$, we have force at distance $\frac{1}{2} = 1{\cdot}4\,a \times 1{\cdot}4\,b = 2\,a\,b$ nearly. Similarly, in decreasing the distance to $\frac{1}{3}$ *p n*, *n* becomes 1·73 *n*, instead of 3 *n*, and *p* becomes 1·73 *p*, instead of 3 *p*, and we have for total force at

distance $\frac{1}{3}$ = $1 \cdot 73\ a \times 1 \cdot 73\ b = 3\ a\ b$, and so on. Thus, whilst the distances are 1, $\frac{1}{2}$, $\frac{1}{3}$, &c., the forces are 1, 2, 3. In this case the reciprocal forces of attraction are as the distances inversely (175), according to the law observed by Muschenbroek (185), cases 1 and 2; Œpinus, Tent. Theor. Electr. et Magn. 301, &c., also arrived at a similar result.

Exp. 54. This law may be fully verified by experiment as in the preceding case, by taking the force and distances within about one-third the sensible limit of action. Thus, with a given magnetic power, the distances being 4 and 2, the forces were 8 and 16. In comparing the distances and forces with magnets of low power, especially in cases of magnets by induction, the forces are generally as the distances inversely. Let, for example, the distance S N, Fig. 79 (130), be made constant, and distance $a\ b$ varied, the reciprocal forces of attraction, between a and b, will be almost invariably as the distances inversely.

217. Should the induced forces in any case vary in some other inverse ratio of the distance, suppose, for example, it should approach the $\frac{3}{4}$ power of the distance, which it may (214), then on diminishing distance to the line $c\ d$, Fig. 106, = $\frac{1}{2}$ distance $p\ n$; force n will become $1 \cdot 68\ n$ instead of $2\ n$, and force p will be $1 \cdot 68\ p$ instead of $2\ p$, and we should have the total force at distance $\frac{1}{2}$ expressed by $1 \cdot 68\ a \times 1 \cdot 68\ b = 2 \cdot 8\ a\ b$ nearly. Similarly at distance $\frac{1}{3}$ it would be $2 \cdot 8\ a \times 2 \cdot 8\ b = 7 \cdot 84\ a\ b$; since, according to the same law, n would become $2 \cdot 8\ n$, and p would become $2 \cdot 8\ p$, instead of $3\ n$ and $3\ p$ (215), and so on. In this case, whilst the distances are 1, $\frac{1}{2}$, $\frac{1}{3}$, the forces are 1, 2·8, 7·8; that is to say, they are in the inverse sesquiplicate ratio, or $\frac{3}{2}$ power of the distances, according to the law deduced by Martin in three very unexceptionable experiments (189): that is to say, at $\frac{1}{2}$ and $\frac{1}{3}$ the distance the forces become nearly 3 times and 5 times as great (176).

Exp. 55. This result may be verified, as in the preceding experiments, by noting the distances and forces within

about $\frac{1}{5}$ and $\frac{2}{5}$ of the sensible limit of action. Thus, at distances 8 and 4, the forces were 5 and 14, being in the inverse sesquiplicate ratio of the distance, or very nearly.

218. When the induced forces vary in any inverse ratio greater than that of the simple distance, we obtain laws of force in an inverse ratio greater than that of the second powers. Let, for example, the induced forces approach the $\frac{3}{2}$ powers of the distances inversely (214), so that on reducing distance $p\,n$ to $\frac{1}{2}$; n becomes $2 \cdot 83\, n$; at distance $\frac{1}{3}$ it becomes $5 \cdot 2\, n$, and so on; instead of $2\, n$ and $3\, n$ as in the first case. And let force p vary similarly, then we have force at distance $\frac{1}{2} = 2 \cdot 83\, a \times 2 \cdot 83\, b = 8\, a\, b = 2^3\, a\, b$; at distance $\frac{1}{3}$ it would be $5 \cdot 2\, a \times 5 \cdot 2\, b = 27\, a\, b = 3^3\, a\, b$, and so on: that is to say, taking $a\, b$ as a unit of force at a unit of distance $= p\, n$, as before, we have at distances 1, $\frac{1}{2}$, $\frac{1}{3}$, the corresponding forces, 1, 2^3, 3^3, &c., that is, 1, 8, 27; by which we perceive, that as the distances decrease, the forces increase in the proportion of the cubes of the distances inversely (175); being the law of force given by Sir Isaac Newton (181).

Exp. 56. We may verify this result experimentally, by taking the forces and distances from about $\frac{2}{5}$ to $\frac{5}{6}$ of the limit of action. The balanced beam, Fig. 107 (212), is well adapted to this experiment; and if we substitute a small magnet for the trial cylinder t, so as to extend the limit of action, then this law will become very apparent. Thus, at a distance of six inches, the force was observed to be 2°; at 3 inches it increased to 16°.

219. By taking the induced forces $p\, n$ in some other inverse ratio (214), we may in a similar way obtain a law of of force, such as found by Brook Taylor, Whiston, and Hawskbee. Suppose, for example, that at distance $\frac{1}{2}$, n becomes $2 \cdot 37$ times as great, and that p varies with it, we should then have the total force at distance $\frac{1}{2} = 2 \cdot 37\, a \times 2 \cdot 37\, b = 5 \cdot 6\, a\, b$ nearly, which would be as the square root of the fifth power of the distance inversely (176), and which result may frequently be obtained in taking the forces and

distances within limits from about the $\frac{2}{5}$ to $\frac{3}{5}$ of the sensible distance of action.

If magnetic forces could be satisfactorily traced to the limits of their vanishing points, we might probably obtain laws of force in the inverse ratio of the fourth or fifth powers of the distances; at least there appears no reason to suppose that the law of the inverse cube of the distance is the ultimate law of this species of force; supposing it to depend on the mutual play of the inductive actions we have described (209, 214).

220. It may be, perhaps, as well to remark here, that in all these laws of force as thus deduced, and which differ from that of the inverse square of the distance, the same result may be arrived at in supposing a limit to one only of the forces (209). If we suppose, for example, the reflected force p, Fig. 106, to change so little at small distances from the magnet, as to admit of being taken as constant. Then the total force would vary with the other; that is to say, it would be as the distance inversely, supposing the direct force to continue according to that law (214). Thus (216), suppose at distance $\frac{1}{2}$, force n became $2\ n$, whilst force p remained unchanged, we should then, calling force at a unit of distance $a \times b$ as before, have the force at distance $\frac{1}{2} = 2\ a \times b = 2\ a\ b$; that is to say, the distances being as 2 : 1, the force would be as 1 : 2. A similar reasoning applies to all the other cases (217, 218, 219). It is, however, more in accordance with observation to suppose the two forces to vary together.

221. The reciprocal attraction between the opposite poles of two magnets differs only, from that of the force exerted between a magnet and iron, in degree of distant action, not in kind. By the presence of permanent polarities in both the opposed surfaces, instead of in one only, the inductions upon which the subsequent attraction depends are greatly facilitated. In the force as exerted between a magnetic pole and mere iron, the pole n, Fig. 106 (209), upon which the reflected

force depends, has first to be produced; that is to say, the magnetic forces resident in the iron (14) must be first developed, and a portion of one of them determined in the direction of the magnet; whereas, in the reciprocal force between opposite magnetic poles, this portion of the attractive process is already complete, and the remaining part is a determination of the opposite forces in each bar in the direction of the opposed poles (210). In this case the limit of the distance at which the forces act is very considerably increased; by employing a small and powerful trial magnet in the balanced beam, Fig. 107 (212), we may obtain indications of measurable force at a distance of 10 inches or more; with delicately suspended needles and large magnets, Scoresby obtained indications of force at distances of 50 or 60 feet.

222. If we proceed to investigate the laws of magnetic repulsion, as exerted between similar magnetic poles (31), we shall find the same mutual play of reciprocal inductive force, as in the case of attraction; with the exception that the tendency of the inductions is in a contrary direction to that of the existing magnetic developments, Fig. 18 (28), and consequently to subvert the opposed poles; now the resistance to this subversion by the already established polarities, is probably the source of the repulsive effect (31). In conformity with this result, if we present to the pole of the magnet M, Fig. 109, whilst acting on the trial cylinder *t*, the similar pole of a second magnet *m*, the force on the trial cylinder will appear to increase. This is in fact the converse of the result already adverted to (213); here the tendency of the induction is (14) to repulse the similar polarity, and so increase its operations in other directions; we could hence deduce the law of this induction by observing the increase or decrease of the force upon the suspended cylinder, as the distance between the two magnetic poles is varied.

Supposing the laws of the inductive force to be the same

as before (214), let the similar poles of two magnets A B, Fig. 106, be opposed to each other, and let the small space n be taken to represent the amount of the subversive tendency on the magnet B, and the small space p that on the magnet A, then calling all the active magnetic particles in $n = a$, and all those in $p = b$, and taking some distance $p\,n$ as a unit of distance, we have, according to a similar notation and reasoning before given (215), force at distance unity $= a \times b$; supposing the induction to vary as the distance inversely, and the polarity to remain unchanged, it will be at distance $\frac{1}{2} = 2\,a \times 2\,b = 2^2\,a\,b = 4\,a\,b$; at distance $\frac{1}{3}$ it will be $= 3\,a \times 3\,b = 3^2\,a\,b = 9\,a\,b$, and so on; according to the law determined by Coulombe (207); that is to say, the resulting force will be as the second powers of the distances inversely, and which may be verified experimentally by means of the two magnetic instruments (212) employed in all the preceding experiments; similar instead of dissimilar magnetic poles being opposed to each other, and a limit of distance being taken, such as does not affect the existing and established polarities. If in this, as in the former case of attraction, we suppose the inductive action to vary (214), then we may obtain laws of force according to other inverse powers of the distance. In fact, we may suppose the induction to be such, as will give any law of force, consistent with the nature of magnetic action. It is not, however, probable, from the peculiar character of magnetic repulsion, that any law of force in a greater inverse ratio than that of the second power of the distance would be likely to obtain, although the force may be frequently found to vary, as is commonly the case, in a less ratio; as, for example, in the inverse ratio of the simple distance, a very common law of repulsive force at comparatively small distances.

223. We have further to observe, that from the circumstance of the total repulsive power being dependent on the permanency of the opposed polarities, and on their relative intensity, we may infer, that in the case of opposed polari-

ties of very unequal force, the weaker may, at some limit of distance, yield to the inductive action of the stronger, and so an opposite, but weak, polarity may become induced upon the subversion of the polarity before existing. In this case the increments in the repulsive force would continue to decline, and the repulsion would at length be superseded by a weak attraction. This result is especially seen in Muschenbroek's experiments before quoted (188), and is easily obtained by means of the hydrostatic magnetometer, with magnets of very unequal force.* Indeed, it is no uncommon case to find two magnets repel at some distances, and attract at others. Even if we employ two magnets of precisely equal power, the tendency is always to a mutual reversion of their poles: and this tendency is so powerful as the distance between them becomes considerably diminished, that in no case do they remain unchanged. Under such conditions, therefore, experiments with repelling poles of opposed magnets would be open to considerable disturbance, and the results, as observed by Muschenbroek, not conformable to any regular law of force (184).

224. On a careful review, then, of these investigations, we find a fair solution of the seeming contradictions and differences in the results of experiments on the law of magnetic force, by many eminent philosophers, alike distinguished for their scientific learning and experimental ingenuity; and they appear to verify, in a remarkably clear and satisfactory manner, the truth of the deduction arrived at by the celebrated Brook Taylor, viz.: "That magnetic attraction, as commonly observed, is quicker at greater distances than at small ones, and different for different magnets;" which taking the facts as they present themselves in the ordinary way, is undoubtedly the case; and is, if the principles we have laid down be exact, not merely an experimental fact, but a necessary result of the elementary laws of magnetism (209, 214).

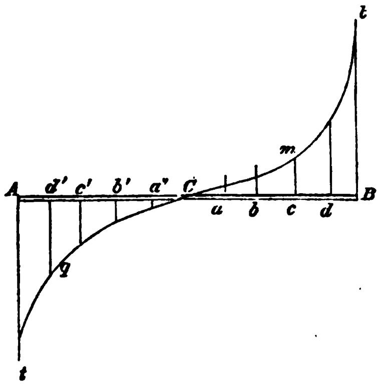
* Edinb. Phil. Trans. for 1829, p. 37.

It is, perhaps, to be regretted, that from a pre-disposition to identify the law of magnetic attraction with that of central forces generally, several profound writers have been led to question the accuracy of every result opposed to such a deduction. Thus, it has been said of Newton, who found the force of magnetism nearly as the cubes of the distances inversely (181), that he had very inaccurate ideas of magnetic phenomena.* It would be very difficult, however, to show from the little which this great author has advanced on this subject in his immortal work, the *Principia*, in what his notions were defective; on the contrary, they appear to be in most perfect accordance with experiment, and true to the letter. In associating magnetic action with a law of the centrifugal forces of particles terminating in particles next them, Newton never pretended to offer any theory of magnetism, but says, with his usual diffidence, "whether elastic fluids do really consist of particles so repelling each other is a physical question," which he leaves philosophers to determine. On the other hand, the learned Dr. Robison is led to question the accuracy of all the results produced by Hawksbee, Brook Taylor, Muschenbroek, and others (182), conceiving them to have been defective and injudicious; and further states, as we have already observed, that magnetic attractions and repulsions are not the "proper phenomena for declaring the precise law of variation." Yet it was by the means of these very same attractions and repulsions that Lambert, and more especially Coulombe, deduced what this accomplished author considers to be the true law of Magnetism.

225. *Law of Force in different Points of a Magnetic Bar.* —We have seen (25) that the polar forces in a magnetic bar decrease rapidly as we recede from the extremities, and at last vanish in a point termed the magnetic centre. If, therefore, we erect, between the magnetic centre and pole, Fig. 110, a series of perpendiculars or ordinates, *a b c*, &c.,

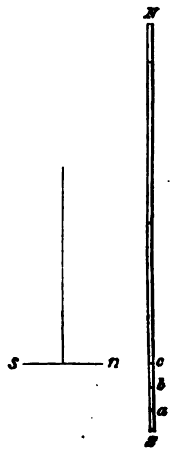
* Edin. Encyclopædia, vol. xiii. p. 270.

Fig. 110.



a' b' c', &c., such as may represent the force in given points, then it is certain these lines will increase rapidly as we approach the poles A B, and we should, in passing a line through the extremities of these perpendiculars, obtain for the force of the north and south polarities, some such curve as that represented in the figure by the lines C *m* *t*, C *q* *t*, the ordinates being nothing in the centre C. Coulombe endeavoured to determine the value of these ordinates in the following way: —

Fig. 111.



Having determined the times of oscillation of a delicately suspended needle, *s n*, Fig. 111, a long magnetic wire, S N, was then placed vertically in the line of the magnetic meridian, immediately opposite the needle, the dissimilar polarities being opposed to each other. This would not of course change the direction of the needle; it would only affect the rate of vibration (139). The needle was now caused to vibrate opposite various points, S *a* *b*, &c., of this linear magnet, and at a constant distance from it. Then, taking the forces as proportionate to the square of the number of vibrations (139), and deducting the constant force previously determined, and by which the needle vibrates when the magnet S N is away, we

obtain the force due to any given point *a*, *b*, &c. In this experiment Coulombe supposes that the resulting force, as thus determined, is very nearly that of the point opposite which the needle vibrates; for, if we suppose the oblique forces of other points *a*, *c*, on each side of a given point *b*, to influence the result, still one-half the sum of the equidistant oblique actions will not be very different from that of the given point *b*; for if the points on one side *a*, are more powerful, those on the other are more weak; and whatever be the nature of the curve c *m t*, Fig. 110, which joins the ordinates, we may consider any very small portion, *m*, as a straight line. When, however, we come to the extremity of the wire or pole s, then, because there is no point outside it, as in the other cases, he doubles the number representing the square of the number of oscillations, by which artifice he renders the experiment for points near the pole comparable with the others. The curve of intensity thus traced by Coulombe, is a species of curve termed the logarithmic curve, the ordinates of which *a*, *b*, *c*, &c., Fig. 110, are in geometrical progression, whilst the abscissæ, c *a*, c *b*, &c., corresponding to these ordinates, are in arithmetical progression.* M. Biot, who treats this question from Coulombe's manuscripts, concludes that this result is a necessary consequence of the law of magnetic force being as the squares of the distances inversely, and that magnetism, like electricity, is little sensible in a body of regular figure before we approach its extremities, when it increases very rapidly.

226. The results and progress of Coulombe's investigation are, it must be admitted, neither so perfect or so satisfactory as could be desired, owing probably to the many difficulties

* That is to say, the abscissæ or distances c *a*, c *b*, c *c*, &c., Fig. 110, increase by the constant addition of some given number 1, 2, 3, &c., as the case may be, and the corresponding perpendiculars or ordinates, *a*, *b*, *c*, *d*, &c., by a continued multiplication by some given number, 2, 3, 4, &c.

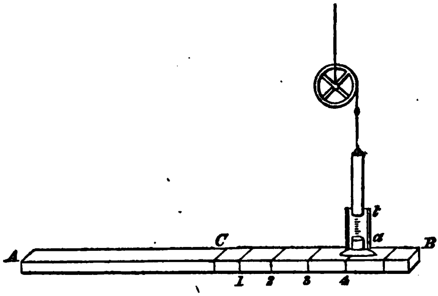
which embarrass the experiment, and the uncertain condition of the line of particles of the steel as to temper and other circumstances. It is therefore doubtful whether the logarithmic curve really represents the law of intensity from the middle point of the axis toward both poles. Lambert considers the force of each transverse element to be directly as the distance from the centre, whilst Robison, who repeated Lambert's experiments, imagines that this is only true for certain magnets. The results of Hanstein's inquiries (208), before quoted, go to prove, that the power of the distance representing the increase or decrease of the magnetic intensity between the centre and the poles of a magnet, agrees most perfectly when that power is taken = 2, or that the intensity of any magnetic particle situated in the axis is proportional to the square of its distance from the middle point of that axis.

227. Much uncertainty appears to have attended these inquiries, in consequence of a want of due attention to the regularity and temper, and the regular development, probably, of the magnetism throughout the bar. It is well known that bars not regularly and equably tempered, or only hardened about the extremities, will not retain any magnetic power except in the tempered parts. In other cases of very long bars, to which an adequate power for their complete magnetizing has not been applied, we have what has been called by Van Swinden culminating points, that is to say, they appear to consist of a series of magnets with opposite poles in contact; added to this, the investigation has been further embarrassed by the methods of experiment; these have been more or less indirect and liable to uncertainty. We may however, by a careful and skilful experimental arrangement, arrive at a fair approximation to the law in question, and in the following way:—

Exp. 57. Let a steel bar, A B, Fig. 112, of uniform texture, about 20 inches long, 1 inch wide, and ·3 of an inch

thick, be very carefully and equably tempered throughout its entire length, and rendered powerfully magnetic by the usual process (20), and in such way as to bring the magnetic centre C (26), as nearly as possible in the centre of the bar. Verify the position of this centre on the upper surface A B, by

Fig. 112.



the process described (28) Exp. 12, and divide that surface on each side the centre C into a given number of equal parts by lines 1, 2, 3, 4, &c., continued down over one side of the bar. These divisions may be about an inch and a half apart. The bar being thus prepared, place it edgeways on the table of support represented Fig. 78 (129), under the trial cylinder *t*, the divided surface A B being uppermost. Examine the forces at successive points 1, 2, 3, &c., through a small cylindrical armature of soft iron *a*, of the same diameter above as the trial cylinder *t*, and about $\frac{3}{4}$ of an inch or more in height, and at a constant distance, *a t*, this armature being fairly applied to the surface, and so as to cover a small space on each side of any given division. The square root of the force thus taken in degrees on the graduated arc of the instrument (126) will very nearly represent the comparative magnetic development. We may, in fact, observe, that by means of the armature *a*, we place the trial cylinder sufficiently beyond the influence of other parts of the bar, whilst the action becomes reduced to two points *a t*, or nearly so. Then, with respect to the armature itself, we may further observe, that supposing the resulting force to be partly derived from

the oblique forces on each side of it, still those forces would be very inconsiderable as compared with that of the point actually covered by the armature. Besides, as remarked by Coulombe (225), if we conceive the points on the side next the centre to be less forcible than those next the pole, still half the sum of all the equidistant forces would come very near the force of the point immediately under the armature, at least for a long series of points, extending from the centre c, but not carried quite up to the extremity of the bar. We may therefore obtain in this way such an approximation as will leave no doubt as to the law we seek to discover.

The experiment thus carried out gave the following results, the distance *a t* being ·3 of an inch:—

Distance from centre	1	2	3	4	5
Force in degrees	1	4	10	17	28
Magnetic development, or square roots of forces	1	2	3·1	4·12	5·29

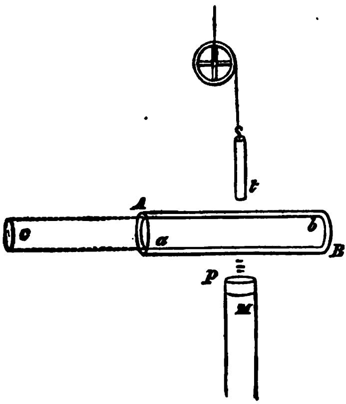
It appears, therefore, by these results, that the magnetism in different points of a regularly tempered and magnetized steel bar, of uniform texture, is directly as the distance from the magnetic centre; whilst the reciprocal force between any given point and soft iron is as the square of the distance from that centre. The distinction is important as regards all the preceding investigations, which may be taken to refer exclusively to what may be termed the intensity (229).

228. *Laws of Magnetic Charge.*—Magnetism, like electricity, appears to be a species of force confined to the surfaces of certain bodies without any relation to their mass. Its accumulation, however, or rather development, in tempered steel, rather partakes of the form of electrical excitation, than that of accumulation on insulated conductors; when developed in soft iron by influence (33), the development is very analogous in character to that of electrical induction by the influence of charged upon neutral con-

ductors. Now, although the terms magnetic charge, quantity of magnetism, and such like, may appear to convey a very hypothetical meaning, they are yet, if taken in the ordinary acceptation of such terms, as applicable to magnetic as to electrical action, since there must necessarily be some element of magnetism corresponding to the general term quantity, as expressive of the relative or absolute amount of the agency in operation, and upon which the observed phenomena depend. We have not, however, hitherto arrived at quantitative measures in magnetism, which, like the unit measure in electricity, determines the quantity of charge conveyed to coated glass. We know not, in fact, by the ordinary processes of magnetizing, what the relative quantities of magnetism may be, as developed in various bars; hence the investigation of such measures is of no small importance to the progress of magnetic inquiry.

By magnetic charge, then, we are to understand the amount or quantity of magnetism existing in a bar of tempered steel or iron, under a given attractive force, and which we may, as in electricity, term intensity. The following experiment shows that this intensity is independent of the mass of a magnetized body; and that consequently the magnetic development is entirely confined to the surface.

Fig. 113.



Exp. 58. Let A B, Fig. 113, be a small cylinder of soft iron, about 2 inches long, $\frac{1}{2}$ an inch in diameter, and $\frac{1}{10}$ of an inch thick. Let *a b* be an interior solid cylin-

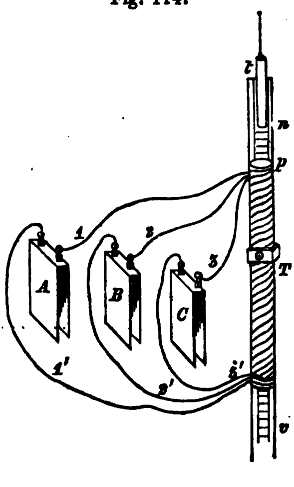
der, also of soft iron, closely applied to the interior surface of the external cylinder A B, but capable of being drawn out to any point c, or otherwise removed altogether. Let now this joint cylindrical mass be attached to a divided scale, and a magnet M, fixed at a constant distance p immediately under it, bring the whole immediately under the trial cylinder t as represented in the figure, and according to the arrangement more fully shown Fig. 77 (129). We may then estimate by the attractive forces on the trial cylinder t any change of intensity in the induced magnetism, the cylinder A B being taken either hollow or solid, or influenced by a greater or less extent of surface c A B. Things being thus arranged, and the distances p and t being regulated to within $\frac{2}{10}$ of an inch, the following results were obtained:—The force, as observed, with the joint cylinders A B and $a\ b$ taken together as a mass, amounted to 10°; under this attractive force, the interior cylinder $a\ b$ being extended toward c, the intensity or force on $t = 10°$ gradually declined; when the surface extended to the greatest limit c the intensity was only $\frac{1}{2}$ as great, the force then being only 5°. On removing the interior cylinder $a\ b$ altogether, the intensity again returned to 10°, being precisely the same as at first. We may hence conclude that Magnetism, like Electricity, is influenced only by surface, and is altogether independent of the mass: a deduction, further supported by the fact that a hollow tempered steel cylinder acquires as great magnetic power by the ordinary process of magnetizing, as a solid tempered steel cylinder of the same dimensions.

229. Magnetism then being a development confined to the surface of magnetic bodies, we require to determine its intensity in respect to the quantity developed, and the extent of surface over which it is disposed. In reviewing the deductions (215) bearing on the law of magnetic attraction, it may be observed that the reciprocal force is always as the square of the induced magnetism; that is to say, as the square of the quantity of magnetism brought into opera-

tion. Thus, where the force is in the inverse duplicate ratio of the distance (215), when induction $= n$, we have force represented by $a\,b$; when n becomes $2\,n$, force $= 2^2\,a\,b$; when n becomes $3\cdot n$, force $= 3^2\,a\,b$, and so on: that is to say, whilst the inductions or quantity of magnetism developed are 1, 2, 3, &c., the reciprocal forces of attraction or intensities are 1, 4, 9, &c.: the same is observable in any of the other laws of force. Take, for example, the case in which the force is as the cubes of the distances inversely (218): when induction $= n$, force is $= a\,b$; when n becomes $2\cdot 83\,n$, we have force $= 2^3\,a\,b = 8\,a\,b = \overline{2\cdot 83}^{\,2}\,a\,b$; when n becomes $5\cdot 2\,n$, force is $3^3 a\,b = 27\,a\,b = \overline{5\cdot 2}^{\,2}\,a\,b$; that is to say, whilst the quantities of magnetism induced are as the numbers 1, 2·83, 5·2, &c., the forces are as the squares of those numbers. We may from this infer, that to arrive at the quantity of magnetism in operation, all other things being the same, we must refer it to the square root of the attraction or intensity.

230. This deduction being a new and important feature of magnetic action, it may be as well to further verify it by something like a direct and quantitative process.

Fig. 114.



Exp. 59. In this experiment let A, B, C, Fig. 114, be three precisely equal and similar voltaic batteries on Smee's principle (47), each battery consisting of two elements, and charged with dilute sulphuric acid. Let T represent a cylinder of soft iron, about 8 inches long, and ½ an inch in diameter, attached to a divided scale $t\,v$, and surrounded

by three distinct coils of copper wire covered with silk thread, not superposed, but coiled successively round the iron. Let the extremities of these coils 1 1′, 2 2′, 3 3′, extend to each of the batteries A, B, C, so as to appropriate each coil to a corresponding battery; for example, coil 1 1′ to battery A, coil 2 2′ to battery B, and so on; the whole being so circumstanced as to admit of an easy connection, and so bring one or more batteries into action at pleasure. Let the iron cylinder T, thus circumstanced, be placed at a given distance *p n* immediately under the trial cylinder *t*, suspended from the wheel of the magnetometer (126) as in the preceding cases; then, as is evident, when either one or more of the batteries A, B, C are brought into operation through their respective coils, the iron T becomes magnetic (53); and hence arises a reciprocal attractive force between its extremity *p* and the trial cylinder *t n*, which force is represented in degrees of the graduated arc attached to the instrument (126). Supposing the batteries to be precisely equal and similar, and each to develop the same magnetic force when taken singly, we may infer that if one battery A, and one coil 1 1′, call up one quantity of magnetism considered as a unit of quantity; then two batteries A + B, and two coils 1 1′ + 2 2′, taken conjointly, will develop two quantities; three batteries and three coils will produce three quantities. To determine the law, therefore, as regards quantity, it only remains to observe the forces of attraction corresponding to these several developments.

The experiment thus carried out gave the following series of results; the distance *p n* being regulated at $\frac{6}{10}$ of an inch.

Batteries or quantity of magnetism	1	2	3
Force in degrees	4	17	37

We may here perceive that the intensity (force) is as the square of the quantity of magnetism, or very nearly; being precisely the same law as that deduced for electrical charge.*

* Rudimentary Electricity, (102), p. 118, second edition.

To obtain, therefore, the relative quantity of magnetism in operation, we must take the square roots of the respective intensities; the magnetic surface and all other things being the same.

231. Although this law appears pretty evident as respects the amount of magnetism in the same or equal magnets, we still require much further investigation of the law of intensity as regards dissimilar magnetic bodies of variable size and surface. The conformity of the previous law of magnetic charge with that of electricity would lead to the conclusion that the law of surface was also the same, and that the intensity would be as the square of the surface inversely;* that is to say, the same quantity of magnetism developed upon a double surface would have only ¼ the intensity. In the present state of magnetic research we can only look to this as being a highly probable result; since we have not any direct methods of experiment, as in electricity, by which such a law can be fairly verified, we require in fact to change the surface without interfering with the magnetism. Now this is not easily accomplished; if, as in Exp. 58 (228), we extend the surface, we are likely at the same time to change the amount of induced magnetism, and we get a mixed result; or if, in the last Exp. 59, we increase the dimensions of the iron cylinder T, we are not sure that the quantity of magnetism will remain the same. Until, therefore, some further means of investigating this question by experiment are at our command, we must be content with considering the law of charge as regards surface in the light of a high degree of probability.

Supposing these laws of magnetic charge so far established, we may conclude that if the respective intensities of two similar magnets, the surfaces of which are to each other in a given ratio, say as 1 : 2 be the same, then the quantities of magnetism in each will be in the same ratio, that is also as 1 : 2; for whilst the intensity increases with

* Rudimentary Electricity, (114) (115), pp. 134, 135, second edition.

the magnetism, it decreases with the surface; and hence with twice the quantity of magnetism upon twice the surface, it remains unchanged; being precisely the same law as that of the accumulation of electricity on coated glass, in which the intensity of a whole battery is no greater than that of one of the elementary jars taken singly.

232. We must not, however, confound this result with a collection of charged jars, or a combination of magnetic bars, each jar or magnet operating independently of the others. What is termed a magnetic battery (19, 115) differs essentially from the electrical battery. It is in fact a mere assemblage of magnets, the resulting intensity approaching in a greater or less degree the sum of the intensities of the whole series; no one magnet forms, as it were, any part of any other magnet; whereas, in the electrical battery, all the jars are united, as it were, into one great whole through the charging rods; and the intensity is no greater in the whole combination than in any one jar taken singly.* To assimilate the action of a number of charged jars with that of a combination of magnets, the jars must be separate, and each brought to operate independently of the others. Imagine, for example, a light-conducting disc, of 6 inches in diameter, poised and suspended from a common balance, then if we place a small charged jar immediately under it at a given distance, the balance will indicate a given force. Let a second similar jar be now placed by the side of the former, then the attractive force will be twice as great, and so on; until we have filled an area exactly equal to that of the suspended disc. We may further conclude that the relative magnetism, in two precisely similar and equal magnets, will be as the square roots of their respective intensities (229), as determined by either of the magnetic instruments (212) employed in these researches.

233. *The Magnetic Curve.*—The two forces developed in

* Rudimentary Electricity, (117), p. 139, second edition.

a magnetic bar, and resident in its surface, give origin in operating on each other through particles of ferruginous matter, to certain curved lines of force, as indicated (28) Fig. 16. These lines were originally considered as the "curvature of the magnetic current," under an impression that they originated in the circulation of a subtle fluid about the poles of the magnet. Although this hypothesis is now but little valued, yet, as observed by Lambert, we must admit the existence of the curves, and may, without any very great violation of language, call them curves of the magnetic current; it is not the name which constitutes the difficulty; whatever name we give them, we have still to determine the nature and properties of the curves.

This very beautiful physical question constitutes, as before observed (202), the principal feature of Lambert's fine mathematical paper in the Berlin Memoirs, and has further engaged the attention of several eminent philosophers. Dr. Roget, the talented author of the treatise on Magnetism, published by the Society for the Diffusion of Useful Knowledge, has also treated this question with considerable ability. Not only has he given many interesting demonstrations of the fundamental properties of the magnetic curve, but has also described a mechanical instrument for generating them.* In referring to Figs. 16, 17, 18 (28), we may perceive that the magnetic curve is either convergent, as in Figs. 16 and 17, or divergent, as in Fig. 18, according as we employ one or more magnets, and according as we refer the forces to similar or dissimilar poles. If we conceive, Fig. 16, each small particle of iron to be an indefinitely small needle free to move in any direction, it would necessarily arrange itself in a given determinate position in respect of the forces in action. In fact, it may be demonstrated, that supposing the magnetic force to vary in the inverse duplicate ratio of the distance, the direction of the

* Journal of the Royal Institution, February, 1831.

axis of a magnetic needle, placed at a given distance from the centre of the magnet, will be always a tangent to the point of curvature of one of those peculiar oval curves indicated in the figure (28). Taking, therefore, the ferruginous particles as indefinitely small magnetic needles, we may conceive the line of curvature at any given distance from the centre as made up of a series of such small needles. With respect to the curve itself, it may be considered, geometrically, as generated by the movement of two lines A C, B C, Figs. 115 and 116, termed radiants, and which revolve about the poles A B, with angular velocities proportional to the varying distances A C, B C, from the point of intersection C. Let, for example, the two radiants A C, B C, be supposed to turn about the poles A and B, and let them have moved together into the positions A *c*, B *c*, then if angle C A *c* be to angle C B *c* as A C to B C, the points C *c* will be points in the magnetic curve.

Fig. 115.

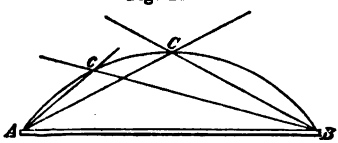
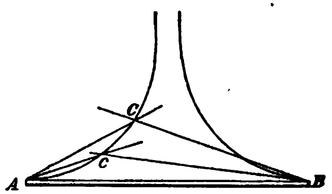


Fig. 116.



The direction of the motion of these radiants, A C, B C, may be, as is evident, either in the same, or in opposite directions. When in opposite directions, as in Fig. 115, both the polar angles, C A B and C B A, increase together, and the curve is convergent; in this case we have a single continuous branch A C B. When, however, the radiants revolve in the same directions as in Fig. 116, then whilst one of the polar angles C B A increases, the opposite angle C A B decreases; in this case the curve is divergent, and

finally resolves itself into two divergent branches, as shown in the figure.

The magnetic curve possesses several very interesting geometrical properties, as may be seen in Leslie's elegant work on Geometrical Analysis;* we have not, however, sufficient space to admit of a more general exposition of this subject. According to one of the principal properties of this curve, the sines of the angles made by a tangent and the radiants, drawn to the point of contact, are proportional to the square of the radiants. Thus, supposing a tangent drawn to the point C, Fig. 115, we should have the sines of the angles formed with C A and C B :: $A\,C^2 : B\,C^2$. In the construction of this curve we require to find points in which a small needle being placed, its direction will be a tangent to the curve.

234. We must not conclude our account of these several inquiries into the nature and laws of magnetic force, without an especial notice of Professor Barlow's very important investigations of the action of spherical and other masses of iron, on the compass-needle, remarkable not only for the precision and elegance of the experiments which they contain, and the mathematical learning and address which they display, but also as furnishing one of those rare examples of physico-mathematical research alike important to the student and to the progress of science.

These researches were commenced soon after the appearance of Hanstein's work in 1817 (208), and were undertaken with a view of correcting the errors arising out of the attractive influence of the iron of a ship on the compass.

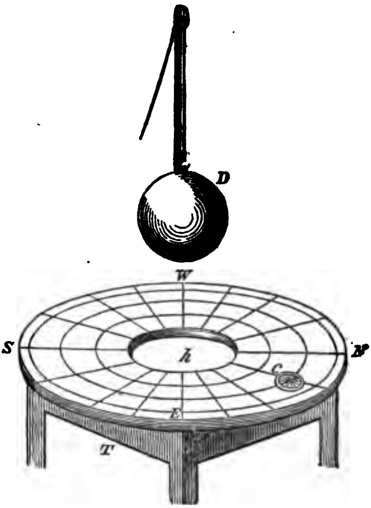
As a preliminary experiment, an iron shell, such as used in the common howitzer mortar, was placed in different positions about a compass (143), considered as a centre of position, and the deviation of the needle noted both as regarded quantity and direction. Now it was soon disco-

* Page 399.

vered that the deviation depended on the position of the centre of the shell in respect of the centre of the needle, the shell being elevated or depressed in a given vertical, so as to place its centre alternately above and below the needle, the deviations of the needle were observed to be in opposite directions; that is, they were first easterly and then westerly, or reciprocally. Now this happened in every azimuth plane (149), except the plane of the magnetic meridian. In this plane the compass maintained its true direction. From these changes in the deviation it followed, that in carrying the shell about the compass, and elevating or depressing it, in different vertical planes, a point would exist in each plane, in which the deviation would vanish, since the deviation could not possibly change from an easterly to a westerly deviation without passing through a point of neutrality. In the azimuth, east and west, at right angles to the magnetic azimuth or meridian, the deviation was nothing at the line of intersection of the magnetic with the horizontal plane, that is in the east and west line. In this line the needle also took its natural direction. Now it occurred to Professor Barlow, that if a great number of points of no deviation were thus determined, they might all be in the same plane, which plane would probably in these latitudes be inclined to the horizon; for, since only two opposite points of no deviation were observed in the horizontal plane, it could not evidently be parallel to the horizon.

235. With a view to a more perfect experimental investigation of this interesting question, Professor Barlow contrived a new form of the experiment. His apparatus is represented in the annexed Fig. 117. A plane table T, about 4 feet 8 inches in diameter, fixed on massive pillars, being covered with fine paper, has several concentric circles drawn on it. The circular plane is divided into 144 equal parts by radii drawn to every $2\frac{1}{2}°$ of the circumference, and all parting from one principal diameter N S, taken in the line of the magnetic meridian. The centre of this table is a distinct

Fig. 117.



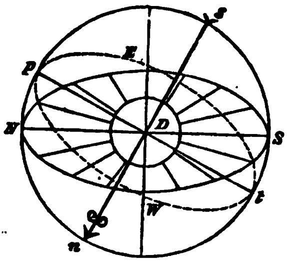
circular piece of 18 in. diameter, which may be removed so as to leave an opening for an iron ball or shell D, weighing about 288 lbs., and hung on a set of Smeaton's pulleys. Things being thus disposed, a compass C is placed on one of the concentric circles of about 20 inches radius or distance from the centre, and the deviations under the influence of the iron ball D observed at each 5°, in different azimuths, that is, in carrying the compass quite round the circle. By elevating or lowering the ball, the height or depth of its centre, above or below the centre of the compass needle, in the various points of no deviation, could be easily determined. The result of this experiment clearly proved that the points of no deviation are all in the same plane, which plane is inclined to the horizon at an angle of about 20°, being the complement of the angle of the dipping-needle (153), that is, the quantity required to complete 90°, the dip being about 70° (158).

It is quite clear that this method of observation is virtually the same as the former (232), the difference being, that we circulate the compass about the ball, instead of carrying the ball about the compass, and instead of elevating or depressing the centre of the needle, we raise or lower the centre of the ball.

236. It may perhaps facilitate the conception of this extremely beautiful experiment, and the results arrived at,

if we suppose the ball D, Fig. 117, to be fixed in the centre of the table T, one half being above, the other half below the plane of the table, as shown in the next Fig. 118, and then imagine the compass to be circulated about the ball. The experiment would then stand as in Fig. 118. In this figure let N E S W be the horizontal plane of the table, D the iron ball. Let *s n* be the direction of the dipping-needle (153), Fig. 92; N *s* S *n* the magnetic meridian, and N S the direction of the horizontal needle. Now

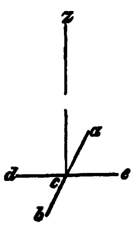
Fig. 118.



we are to suppose the compass to be circulated about the ball D in a circle of a given radius, say 20 inches, and its centre elevated or depressed above or below the horizontal plane at each azimuth of 5° (149), as the case may be, until the deviation vanishes. In this case the centre of the compass would be found to have moved in the plane *t* E *p* W, inclined to the horizon N E S W, about 20°, and perpendicular to the direction *n s* of the dipping-needle.

Our conceptions of this experiment may be still further enlarged, if, instead of the horizontal needle, we suppose a small dipping-needle to be circulated about the ball, prepared as in the annexed Fig. 119; in which, let *a b* be a very small magnetic needle, centrally suspended by a delicate thread *z c*, and crossed at the centre *c* by a horizontal index *d e*, consisting of an extremely light reed, or a bristle. If this needle be circulated about the ball D, Fig. 118, as before, the index *d e* will exhibit the same deviations as the horizontal needle, whilst the relative position of the inclined needle in respect of the polar axis

Fig. 119.



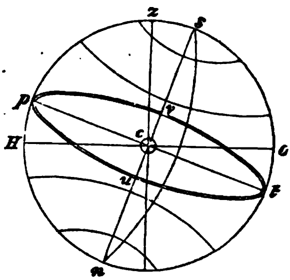
n s of the ball D, will materially assist our comprehension of the results.

Let us then imagine this needle, *a b*, Fig. 119, to be in the point W, Fig. 118; it will in this point have no deviation (234); here the line of direction or axis of the needle being parallel to the polar axis *s n* of the ball, and the line D W, joining their centres being their perpendicular distance, all the attractions upon the needle will balance. Directly, however, we move the needle out of this position, the same conditions do not arise, except the centre of the needle move in the plane W *p* E *t*. It is only in this plane that the direction *a b*, Fig. 119, of the needle, and the polar axis *s n*, Fig. 118, of the ball D, remain parallel, and their centres always at the same perpendicular distance. We see, therefore, why it is that the points *p t*, in the magnetic, and points E W, in the horizontal plane, are points of no deviation. They are, in fact, all points in the plane of equal attraction, or neutrality, as we may also term it. The east and west points in the horizontal plane are the points of intersection of the two planes. There is, however, this difference between the inclined and horizontal needles when placed in the magnetic plane N *s* S *n*; except in the points *p s t n*, the inclined needle varies, in the course of circulation about the ball D in that plane, much in the same way that the horizontal needle deviates in being carried round the ball D, in the horizontal plane. Now every point in the magnetic plane is a point of no deviation for the horizontal needle (234), but not for the dipping-needle (236); hence, for the horizontal needle we have two planes of no deviation, the inclined plane *p* E *t* W, and the magnetic plane N *s* S *n*. It is, however, the inclined plane which we are to consider as the plane of no deviation *par excellence*, because in this plane neither the dipping-needle nor the horizontal needle deviates, whereas in the magnetic plane there are only four points of no deviation for the dipping-needle, viz., the

points *p* E *t* W, and these are, after all, points in the plane of neutrality; besides this, the cause of no deviation of the horizontal needle in the magnetic plane is of a very different kind from that of the cause of no deviation in the inclined plane, which has a peculiar and distinctive character.

237. Since the neutral plane evidently cuts the surface of the ball in a great circle, *p u t v*, Fig. 120, the plane of which passes through the centre C,—this great circle has been called by Professor Barlow the magnetic equator, the axis and poles of which are coincident with the line *s n* of the dipping-needle. The hemisphere *p n t*, below the equator *p t*, he calls the north magnetic hemisphere, and the opposite hemisphere, *p s t*, the south magnetic hemisphere. Any point on the sphere is distinguished by its magnetic latitude and longitude, to which end, parallels of magnetic latitude and meridians of longitude are drawn, as on the common globes. Extending the plane of these circles, they may be conceived to cut an ideal sphere, *p s o n*, concentric with and surrounding the ball *c*, and may be hence employed to define the magnetic position of any point in space with reference to the centre *c* of the sphere.

Fig. 120.



In circulating a compass about the ball in any of these lines or circles, Professor Barlow found, as he had anticipated, that the greatest amount of deviation was in the meridian circle passing through the east and west points; on this account he takes this meridian as his first meridian, and calls its longitude zero. Instead of imagining an ideal astronomical sphere, *p s o n*, to surround the ball *c*, and in given points of which the compass may be supposed placed, it will be in some cases more convenient to imagine such a

sphere to surround the centre of the compass placed at *c*; and suppose the ball moved into certain points of longitude and latitude, the practical result will be evidently the same, and reference may be made to either at pleasure.

238. Very numerous experiments and comparisons between the trigonometrical lines (182) of the angles of deviation and those of the latitude and longitude of the point in which the compass or ball is placed give the following results; and which apply to regular as well as irregular masses of iron.

1°. The longitude being zero, that is the compass or ball being anywhere in the great circle passing by the east and west points (235), "the tangent of the angle of deviation is proportional to the sine of the latitude multiplied by the cosine, or to the sine of the double latitude." *

2°. The latitude being constant, "the tangent of the deviation is proportional to the cosine of the longitude."

3°. The latitude and longitude being both varied, "the tangent of the deviation is proportional to the cosine of the longitude multiplied into the sine of the double latitude."

If we denote the deviation by Δ, the latitude by λ, and the longitude by l, we have these laws thus algebraically expressed:—

$$\text{Tang. } \Delta = \sin. 2\lambda. \quad \text{Tang. } \Delta = \cos. l.$$
$$\text{Tang. } \Delta = \sin. 2\lambda \times \cos. l.$$

The laws of attraction with respect to distance and force, were found to be as follows:—

$$\text{Tang. } \Delta = \frac{1}{d^3}. \quad (\text{Tang. } \Delta)^2 = F^3. \quad \text{Tang. } \Delta = F^{\frac{3}{2}}.$$

in which the distance is denoted by d and the force by F.

It is to be understood that these laws are only calculated approximatively, they are positively correct only for a needle indefinitely small, and placed at a limit of distance from the iron ball, such that the magnetism of the needle, and that

* The product of the sine and cosine of an angle is = to the sine of twice that angle.

of the ball, as depending on the induction of its position (101), may operate on each other in the way of two magnets. If we bring the needle very near the ball, then the induction of the magnetism of the needle upon the iron is such as to supersede this action; and instead of attracting one pole of the magnetic needle and repulsing the other, it will attract either pole of the needle indifferently, or nearly so (222).

239. This action of an iron ball on the compass-needle, contrary to Professor Barlow's expectations, was found independent of the mass, and to relate only to a small thickness of surface. The following are the results as regarded balls or shells of different magnitudes:—

1°. The tangents of the deviations are proportional to the cubes of the diameters of the shells or balls; so that we have, in denoting the diameter by D, Tang. $\Delta \propto D^3$.

2°. The tangent of the deviation is as the $\frac{3}{2}$ power of the surface. Hence, if we denote the surface by S, we have Tang. $\Delta \propto S^{\frac{3}{2}}$.

These laws are apparent whatever be the weight or thickness of the shell, provided its thickness be not less than the $\frac{1}{30}$ of an inch.

Although the conclusion that Magnetism resides wholly on the surface of iron bodies appeared satisfactorily established in this kind of action, yet Professor Barlow considers "further experiments necessary to establish the fact." Such experiments we have already adduced (228), and they confirm in a very striking way the truth of this deduction.

Our limits will not admit of any further account of these most valuable researches into the laws of magnetic forces, which the student will find very clearly and explicitly detailed in Professor Barlow's work on "Magnetic Attractions." We shall, however, have again occasion to refer to their practical and theoretical application under another branch of our subject.

VII.

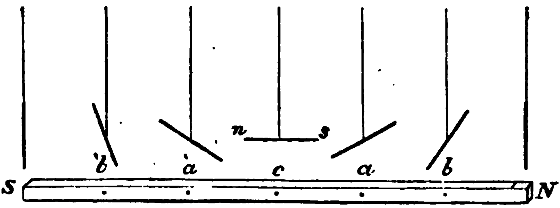
TERRESTRIAL MAGNETISM.

The Earth a Magnetic Body—Variation, Dip, and Intensity, the three Forms of its Magnetism—Phenomena of the Horizontal, Inclined, and Oscillating Needles—Variation of the Compass—Magnetic Charts—The three kinds of Magnetic Lines—Course of the Terrestrial Magnetic Equator—Points of greatest Polar Dip—Points of greatest Polar Intensity—Position of the Magnetic Poles—Magnetic Disturbances.

240. Comparing the phenomena of the horizontal and inclined needles (21) with those of ordinary magnetic action, we can scarcely avoid the conclusion that the globe of our earth is upon the whole a magnetic mass, and that it operates on those needles much in the same way as one magnet operates on another. We have seen (153) that in these latitudes the position of an evenly-poised and freely-suspended magnetic bar is not a horizontal position, but an oblique position, the north pole being inclined downward at an angle of about 69° with the horizontal line. Now, if we transport this bar to various parts of the earth, then this angle or dip varies, being nothing about the equatorial regions, where it is horizontal, and 90° in the regions of the poles, where it is vertical (21), that pole of the bar which turns toward the north being depressed in the northern hemisphere, and the opposite pole in the southern hemisphere; the following experiment is highly illustrative of the magnetic conditions of this phenomenon.

Exp. 60.—Let N S, Fig. 121, be a magnetic bar, 30 inches in length, about ½ an inch thick, and 1 inch wide, we are to suppose this bar regularly magnetic and laid edgeways. Let *n s* be a short balanced needle of light iron wire or

Fig. 121.



magnetic steel wire, about 2 inches in length, suspended by a filament of silk, immediately over the magnetic centre c, so as to be a full length distant from it. At this point the needle will retain its horizontal position, its axis being parallel to the axis of the magnet beneath, and its poles *n s* in a reverse position to the poles N S of the bar (11). Under these circumstances let this small needle be gradually moved along, and over the magnetic surface N S, we shall then find it take different degrees of inclination, the inclination being greater as we approach either pole N S, at which points it will be 90°. We shall further observe, in the course of this experiment, that the south pole *s* dips on the north polar side of the centre c, and the north pole *n* on the south side. We have here only to conceive the longitudinal magnet N S to represent a portion of the earth's surface extending between the polar regions, and we have a series of phenomena very analogous to those of the direction and dip of the magnetic needle (21).

The magnetism acquired by a bar of soft iron when placed in a given position (101) is further indicative of the magnetic state of our planet. We have already seen (102), that, in placing a bar of soft iron in the position of the dipping-needle, it is immediately rendered sensibly magnetic; the lower extremity in these latitudes being a south pole, and the upper extremity a north pole. If the experiment be tried in the southern hemisphere, then the lower

extremity becomes a north pole, and the upper extremity a south pole. Now this is as near an approach to magnetic induction (33) as can be well imagined.

241. This magnetic condition of our planet, from whatever source derived, becomes more fully revealed to us through the medium of three classes of phenomena, viz., variation (7) (162), dip (21) (162), and intensity (228); these are the three great forms of the earth's magnetism. The absolute values of these elements, the changes to which they are subject, together with their mutual relations and dependencies, have now become the great objects of investigation, we may add to these certain irregular disturbances by which these elements are occasionally influenced, and which are more especially traced by means of the magnetic instruments and observatories already adverted to (169). In order, therefore, to investigate the magnetic condition of the earth, we require to know

1°. The declination or variation of the horizontal needle, by which we determine its correct position or direction at any given place.

2°. The inclination or dip, by which we determine the true line of direction of the magnetic force.

3°. The number which represents the ratio of the intensity of the force at any given place, to some comparative unit, by which we trace the general magnetic condition of the terrestrial surface.

242. The changes to which the earth's magnetic force is subject may be distinguished by the terms secular, periodical, and irregular. Secular changes are such as are slowly progressive and which run through a certain course in very long periods of time, returning finally to their original value. Periodical changes are certain regular changes or variations, happening in short periods of time, such as a day, a month, or even a year. Irregular changes are such as cannot be traced through any uniform

course and which are not apparently subject to any given law.

243. In pursuing this most important physical subject, we cannot do better than commence with the phenomena of the horizontal needle. Did the magnetic compass everywhere coincide in direction with the geographical meridian, and were its direction invariable, it would be one of the most simple and valuable instruments ever constructed; such, however, is not the case (162), its direction is not everywhere the same, it seldom coincides with the true meridian, and is beside subject to a variety of periodical and other variations.

The angular deviation of the compass from the true meridian, termed the declination or variation of the magnetic needle, was certainly known to the Chinese so long since as the commencement of the twelfth century. Keoutsoung-chy, a Chinese philosopher, who wrote on subjects of natural history about the year 1111, states that "the magnetic needle declines toward the east, and hence does not point straight to the south, but is only $\frac{5}{6}$ to the south." Pere Amiot, who resided at Pekin about the year 1780, remarks, in confirmation of this, and in reference to the north pole of the magnet, "the magnetic needle still persists in this capital in pointing 2° and 2° 30′ towards the west, which is still a peculiarity of this country." The Chinese say, in reference to the south pole, that "the needle declines eastward 2° and 2° 30′, that it is never more than 4° 30′, and never less than 2°."* An old manuscript in the University of Leyden, written in 1269 by Peter Adsiger, also notices the phenomenon of an east declination in the north pole of the needle.† The great Venetian pilot, Sebastian Cabot, in the service of Henry VII. of England, also Gonzales Oviedo and the celebrated Colum-

* Klaproth, Lettre à M. le Baron de Humbolt, p. 69.

† Cavallo on Magnetism, p. 317.

bus, and other early enterprizing navigators, all observed the deviation of the compass from the true meridian; indeed it could scarcely have escaped their attention, since they pursued tracts in the course of which the needle must have changed more than two points; the fact appears to have caused no small confusion and anxiety amongst the sailors who accompanied Columbus in his first voyage to America, the needle having hitherto been always supposed to point true north. It appears by Irving's most interesting work,* that, on the 13th of September, 1492, Columbus at nightfall found his needle pointing 6° to the west of the polar star. He again examined this deviation the next night, and found it to increase as he advanced—a circumstance which caused the greatest consternation and alarm; "it seemed as if the laws of nature were changing, and that the compass was about to lose its mysterious power." Columbus, however, quieted the fears of the pilots by telling them that the needle had its daily changes round the pole like the heavenly bodies. It is not a little remarkable that notwithstanding the frequency of these observations, mathematicians and others of that time who adhered to the system of the Aristotelian philosophy, gave little or no credence to these accounts, considering the thing impossible. At length, however, repeated observation no longer allowed the mere abstract philosopher to maintain the discussion, and in 1556 the declination of the compass was fully received by Spanish writers on navigation as an established fact.†

244. The first well-authenticated observations on the variation of the compass in England are to be found in a work by Borough,‡ comptroller of the navy in 1581, as also in a work by Norman, of the same date.§ They state, from observations at Limehouse in 1580, that the declination was

* Life of Columbus.
† Arte de Navegar. Valladolid, 1545.
‡ The New Attraction.
§ Discourse on Variation of Compass.

at that time 11° 15′ East. In the early part of the following century, Professor Gellibrand found the declination to be only 4° 5′ East; and in 1657 it appears to have vanished altogether. From that time to the year 1660 the magnetic needle did not sensibly deviate from the true meridian. About five years subsequently to this (viz. in 1665), the direction of the needle appears to have become about a degree and a half west of the meridian; and this westerly declination went on increasing up to the year 1818, since which time the needle has been again approaching the true meridian. The following table contains the declination with the mean rate of motion as referred to certain periods of observation in London between 1580 and 1850, comprising about 270 years.*

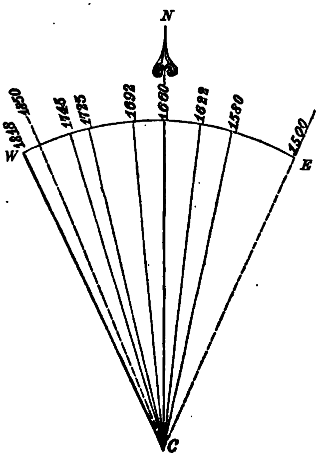
	East declin.		Zero.	West declination.				
Years......	1580.	1622.	1660.	1692.	1730.	1765.	1818.	1850.
Declination..	11° 15′	6°	0°	6°	13°	20°	24° 41′	22° 30
Rate per year	7′	8′	10′	11′	11′·5	9′	0′	5′

It may be perceived by this table, that for a period of eighty years from the first discovery the needle gradually approached the true meridian, and then for a following period of 158 years it travelled westward; having at the end of this period attained, in 1818, its maximum of westerly declination, viz., nearly two points and a half of the compass; it has ever since been retrograding, and is now moving again eastward. The mean rates of the movement at the different periods, although deduced from a long interval of years, may not upon the whole be far wrong; they serve at least to prove that the motion is not uniform. In approaching the meridian it has evidently become accelerated, and in approaching the maximum has become retarded; the present rate of decrease, as deduced by Dr. Lloyd at Dublin, is about 5′ annually. Thus it appears that the horizontal needle is

* The rate of movement has been deduced from the average rates of the intermediate periods.

subject to a variable oscillation across the line of the true meridian; the period of its westerly movement being about 160 years, and the limit of its angular variation 24° 41′. The annexed Fig. 122 represents this angular movement as hitherto observed, the extent of the whole movement being represented by the angle W C E, about 50°, that is, supposing the easterly semi-oscillation to have been equal to the westerly, and the first observations to have been made during the progress of the approach of the needle to the meridian C N, in the year 1580; this would make the total period of one oscillation about 320 years.

Fig. 122.



Observations made at Paris and other parts of the world give similar results; the direction and extent of the deviation, however, are not the same for all places; whilst in particular regions of the globe the needle is found to coincidé always with the line of the true meridian. At this present time the declination is west throughout Europe. As we approach very high latitudes, the disturbance in the direction of the magnetic needle is very considerable. Parry, in his first voyage, observed a westerly declination of more than nine points of the compass.

245. A large number of observations on various parts of the earth, from the poles to the equator, on the sea and on land, prove that the lines of direction of the horizontal needle over the earth's surface are not alike. 2. That these lines are in a constant state of variation, some toward the east, others toward the west.

We are indebted to Halley, who was sent out by the government of William and Mary, to make observations on magnetic declination, for the first attempt to systematize the different variable directions of the magnetic needle. His method consisted in first marking on a general map of the world all those places in which the declination was nothing, and uniting the whole by a line, which he termed the line of no declination. He then traced in a similar way all the points in which the declination was 10°, 15°, 20°, and so on, east or west, thus representing by a magnetic chart the variation of the needle upon the surface of the earth so far as then ascertained, viz. in the year 1700. Many interesting and important results were derived from this system. It was observable, for example, that a line of no variation ran obliquely over North America across the Atlantic Ocean. Another line of no variation descended through the centre of China and passed across New Holland. From which he inferred that these lines had a communication near both poles of the world. Between these lines of no variation, that is, throughout all Europe, Africa, and the greater part of Asia, the declination was observed to be westerly, and on the opposite side, that is, over all the Pacific, it appears to have been at that time easterly. It was further observable, that the lines of greatest variation were confined to the polar regions, whilst the least encompassed the globe about the equator.

246. Lines of equal or of no declination, as thus traced on the earth's surface, have been called "Halleyan lines," in honour of their inventor; and more recently "Isogonal lines," or lines of equal angles. The map or chart on which these lines are traced has been termed a "variation chart," and is evidently an invention of no mean importance to the purpose of navigation. The first chart of this kind, constructed by Halley, has necessarily become obsolete, not only from errors arising from the imperfect state of magnetic instruments at the time of the observations,

but also from the now known variable state of the earth's magnetism. Halley's chart was first revised by Messrs. Mountain and Dodson, about 1756. Since this period we have had the magnetic atlas of Churchman, up to the year 1800, Hanstein's celebrated chart, published in 1820, and the variation chart and globe of Professor Barlow, which includes the observations of Captain Sir James Clarke Ross in the Arctic Seas. The latest chart of this kind is a chart by Erman, who has determined, from his own observations principally, the isogonal lines up to the years 1827 to 1830, throughout the whole length of the Russian empire; these later productions comprehend, not only the variation, but also the phenomena of the inclination and intensity of the force, and may be hence more properly denominated general magnetic charts than charts of mere variation.

The isogonal lines, as thus laid down on a chart, present to the eye a great variety of complicated flexures; they are seldom parallel to each other, a great portion of them appear to converge towards two points on the earth's surface, one near Baffin's Bay, the other to the southward of New Holland. In Hanstein's chart the isogonal lines exhibit a double convergence in the northern hemisphere toward two points in the vicinity of the pole indicated by the dipping-needle.

247. It has been ingeniously observed by Euler, that a perfect variation chart, continually brought down to the latest times, would materially assist in determining the longitude. Imagine, for example, that we found ourselves in a certain place on sea, or in an unknown region, we should first determine the variation of the compass, either by a meridian line or some other method already described (162), suppose the declination to be 5° East; this determined, we seek in the chart for the two lines under which the given declination is found,—we may then be fully assured of being under one or the other of these lines. If we now determine

our latitude, which is easily done, nothing remains but to mark on these two lines of 5° easterly variation, the two points of equal latitude; now the circumstances of the voyage would decide in which of these points we were placed, since they would necessarily be very far removed from each other; a means of determining the longitude by the variation of the needle, was in fact a main object of Halley's expedition.

248. Beside the great secular or progressive movement (244), the magnetic needle is found to exhibit a sensible change from month to month, from day to day, and even from hour to hour. This important fact of the daily variation of the needle was first announced in 1722 by Graham, a celebrated optician of London, who observed that whilst the needle was annually changing its direction, its north extremity advanced westward in the early part of the day, and returned again in the evening eastward to the same position. The amount of this daily variation amounted then to about half a degree. Since this time the fact has been completely investigated by very refined means of observation (163), and the following general results arrived at:—The north pole of the needle begins between 7 and 8 A.M. to move westward, and this movement continues until 1 P.M. About this time the needle becomes stationary, and soon begins to retrograde east, but with a slower motion than that of its previous advance. About 10 P.M. the needle is again stationary at the point from whence it started. A smaller second oscillation now ensues during the night; the north pole moves slowly west until 3 A.M. and then returns again as before. The mean daily changes in this country, as observed by Beaufoy, and lately by Dr. Lloyd, amount to about 9·4 of a degree. The action of the sun is undoubtedly the cause of this daily disturbance of the magnetic needle; we may hence expect it to vary in different latitudes both as to time and extent; we require, however, further observa-

tion for determining whether the daily variations have the same direction in points of westerly declination, as in points of easterly (245). In the southern hemisphere the direction of the daily oscillation is reversed, the north end of the needle here advances eastward and returns westward.*

The annual periodical variation of the needle was discovered by Cassini in 1786, who found that the North Pole, from the vernal equinox to the summer solstice, moved eastward, and again retrograded west during the next nine months. This last motion, however, he found to exceed the previous easterly deviation, and constituted the yearly secular change.

The direction of the horizontal needle is in no degree affected by its energy as a magnet, whether possessing a strong or weak magnetic power, still its direction and all the laws of its variation remain the same; at least so far as hitherto observed.

249. *Phenomena of the Inclined Needle.*—The series of magnetic phenomena of the earth's magnetism which next claim our attention, are those of the magnetic dip or the inclination (21). Mr. Robert Norman, a celebrated optician of London, about the year 1756, having accurately poised some small compass-bars before touching them with the magnet, found subsequently, that when rendered magnetic, they all lost their balance, and assumed a certain angular position in regard to the horizon, so much so that the fly or card attached to them (148), required a counterpoise: this most important discovery naturally excited very intense interest as materially affecting the mariner's compass, and led the discoverer to construct an instrument by which the full amount of this inclination could be correctly estimated, and which he found at that time in London, viz. in 1756, to be nearly 72°. We have already described the nature of this instrument termed the

* Macdonald, Phil. Trans. 1796.

dipping-needle (153); we have now to consider its practical application to the purposes of scientific discovery.

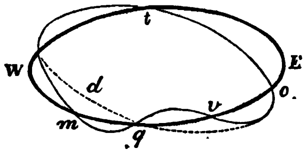
The attention of mariners having become directed to the inclination of the needle, and the fly or cards of the compass as adjusted in London being found to lose their horizontality by a change of latitude, it soon became apparent that the inclination was not everywhere the same, until, as already observed (240), it was finally found to be least in the equatorial and greatest in the polar regions of the earth. Following out Halley's comprehensive views of lines of equal variation, the next great step in the construction of magnetic charts was the addition of lines of equal inclination; these have been termed isoclinal lines, and portray the course of equal dip in all those parts of the world in which observations have been effected.

250. *The Magnetic Equator.*—In uniting in this way all the points in which the inclination vanishes, that is, all the points in which the dipping-needle (153) is horizontal, we trace in the equatorial regions of the earth the course of a most interesting and important circular line, which we may consider as the magnetic equator. This line, as hitherto determined, appears embarrassed by disturbances arising not only from almost unavoidable imperfections in magnetical instruments and the means of observation, but likewise from the presence of ferruginous and magnetic masses in certain portions of the earth itself. Sir James Ross observes of the island of Trinidad, "As a magnetic station our observations were here utterly valueless. Three dipping-needles, placed at only just sufficient distance to insure their not influencing each other, indicated as much as 3° difference of dip."* This appears also to have been the case at St. Helena, and all volcanic islands.

The magnetic equator, as hitherto traced from a large mass of observations by Cook, Bayly, Dalrymple, and other navigators, discussed by Biot, Morlet, and Hanstein, would

* Antarctic Voyage.

Fig. 123.



seem to be an irregular circular line crossing the terrestrial equator in at least three, if not four points. Thus, in the annexed Fig. 123, if we suppose the circle W *t* E to represent the terrestrial equator, then the irregular circular line *m t o* may be supposed to be the magnetic equator, evidently portraying between the points *w* and *o* either some great irregularity in the earth's magnetic condition, or the presence of some great disturbing force. From the great regularity in all the other portion of the curve, we can readily conceive its continued progress through the dotted line *d*, supposing the sources of disturbance we have adverted to not to exist. Duperry, who crossed the Magnetic Equator in the *Coquille* no less than six times during the French expedition of 1822 to 1825, and to whose indefatigable zeal and ability we are indebted for a most careful investigation of this great physical problem, has given, in the Annales de Chemie for 1830, a valuable magnetic chart, representing, according to his researches, its general course. Duperry traces this great magnetic curve, from his own observations alone, through an extent of 247° of west longitude, comprising the Atlantic Ocean, part of South America, the great Equinoctial Ocean, or Pacific Ocean, as far as the west side of the island of Borneo. After this he relies on the observations of Colonel Sabine at St. Thomas in 1822, and of Captain J. de Blosselville* in the *Chevrette*, made in 1827. Adopting the eastern node, as determined by Sabine, which he places in long. 3° 20′ East of the meridian of Paris, in the Atlantic Ocean, not far from the west coast of Africa, the points of no inclination pass through Africa, and ascend into the northern hemisphere, probably up to the

* This most accomplished French navigator has since perished in exploring the frigid regions of the Arctic circle.

fifteenth degree of north latitude, so far as the Red Sea; then, descending through the Indian Ocean, they cross the southern extremity of Hindostan, the isles of Malacca and the northern extremity of Borneo; then traversing the great Pacific, they cross the equator of the globe in a second point, in about lon. 176° East of Paris; so that, according to this course, the magnetic equator is inclined to the equator at an angle of between 14° and 15°, crossing it in two points, nearly diametrically opposite. It is not unworthy of remark, that four-fifths of this great circle traverses the vast seas of the equatorial regions. Although the curve is certainly tolerably regular throughout at least one-half its course; yet a large amount of observations for all that portion running through the Pacific from 112° to 270° of west longitude, tend to involve it in inexplicable windings, such as shown in Fig. 122. By a careful analysis of the observations, recorded at long intervals of time, the nodes or points of intersection of the magnetic and terrestrial equators have a slow westerly movement.

251. The isoclinal lines, or lines of equal dip, relative to all that portion of the magnetic equator, w *t* *o*, Fig. 123, which appears perfectly circular, are upon the equidistant parallels fairly regular, and the dip pretty constant for the same parallel at least up to 60° of magnetic latitude (237). These parallels comprise Europe, Africa, the Atlantic, and the eastern shores of America. Biot, by a refined analysis, has given a formula for the inclination, which appears to represent the phenomena of the dip in some parts of the earth, with a fair degree of precision. According to this formula, the inclination of the magnetic needle in any place is twice its magnetic latitude, a deduction first arrived at by Kraft, of St. Petersburgh. Thus the magnetic latitude of Quito, in Peru, being 6° 33′ 10″, the inclination should be 13° 6′ 20″, that is, double this angular quantity. Now Humboldt gives the dip at Quito, from observation, 13° 21′ 54″, which is a fair coincidence. Barlow, considering

the magnetic condition of the earth as approaching that of a soft iron ball (234), arrives at a similar deduction; according to his formula, "the tangent of the dip is double the tangent of the magnetic latitude." It is, however, very doubtful whether such formulæ can be satisfactorily applied to the whole terrestrial surface, more especially in the present imperfect state of these inquiries.

The following table exhibits the inclination of the magnetic needle as determined at a few remarkable places of the globe, within a comparatively recent date.

SOUTHERN HEMISPHERE.

Place ..	Charlotte Sound.	Cape of Good Hope.	Lima.	Peru.	Alexandria.
Dip......	54° 50′	34°	10° 30′	0° 0′	31° 12′

NORTHERN HEMISPHERE.

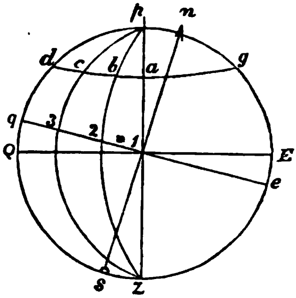
Place ..	Rome.	Paris.	London.	Petersburgh.	Hudson's Bay.
Dip	60°	67°	69°	71°	89° 57′

It is evident from this table that the magnetic inclination increases as we approach the polar regions (240).

The isoclinal lines appear to form irregular oval curves, diminishing in magnitude in each hemisphere as they recede from the magnetic equator.

252. Were the mass of the earth regularly magnetic, having its axis and poles of revolution at a given angle with the magnetic axis, we might possibly in this case derive from the dipping-needle a means of determining the longitude, for the parallels of magnetic latitude (237) would then cut the parallels of geographical latitude and meridians of longitude obliquely; hence all the points of longitude, in the same parallel of terrestrial latitude, would give a different dip; as being at different distances from the magnetic equator (248). Let, for example, $p\ z$, Fig. 124, be the axis of revolution, and $s\ n$ the magnetic axis. Let E Q be the terrestrial,

Fig. 124.



and $e\,q$ the magnetic equator; take any geographical parallel $d\,a\,g$, and any given meridians of longitude, a, b, c, d. Then, as is evident, the points of longitude, a, b, c, d, taken upon the same parallel, $d\,a\,g$, will be unequally distant from the magnetic equator $e\,q$; hence the inclination will be different in these points (248); that is to say, the latitude being known, the longitude would be a function of the magnetic dip, and would increase or decrease with the distance of the given point from the magnetic equator; although the imperfect state of our knowledge of terrestrial magnetism does not admit of a practical application of this method, it may still prove valuable in some particular cases, and is very worthy of further consideration.

253. The magnetic dip, like the direction of the horizontal needle (242), is subject to continual and progressive changes, both secular and periodical, and is at this present moment rapidly decreasing. According to the records handed down to us by different observers in the pages of the Phil. Transactions, the inclination at London in 1576 was 71° 50′. In 1676 it had become 73° 30′. In 1723 it was 74° 42′, having here reached a maximum. In 1790 it had decreased to 71° 53′. In 1800 to 70° 35′. In 1821 the magnetic dip, as determined by Sabine, was 70° 3′. In 1830 Captain Kater gives it as 69° 38′. According to the observations made at the Royal Observatory, Greenwich, it is now about 68° 30′; having decreased about 6° 12′ in 128 years, or at the rate of about 3′ each year nearly. If the early observations are to be relied on, the magnetic dip, when first observed by Norman in 1576, was increasing, and had attained a maximum in 1723, having increased about 2½° in 147

years; being at the rate of about $1\frac{1}{4}'$ annually. Since this it has continually decreased, and with increasing rapidity. The mean annual movement from 1830 to 1850 being at the rate of more than 4′ each year, whilst the first annual decrease between 1723 and 1790 was only at the rate of about 2·5′ annually. Admitting some sources of error in the earlier observations, there is still sufficient evidence of an accelerated and retarded movement in the secular changes of the inclined needle.

The inclination like the declination appears subject also to a slight hourly variation; it is, however, very small. According to Hanstein, the inclination is about 4′ greater in the morning than in the afternoon.

The inclined needle, like the horizontal needle, is not affected by its power as a magnet as to direction; whatever be the magnetic force, the angle of inclination remains the same under the same circumstances.

254. *Needle of Oscillation, or Magnetic Pendulum.*—Although the phenomena of the variation and inclination of the magnetic needle pourtray, under two peculiar forms, the general distribution of magnetism throughout the earth considered as a magnetic body, yet these forms are not so well adapted to convey so definite a view of the magnetism of our planet as would be obtained by an adequate examination of the relative magnetic intensity of different points of its surface. A large number of facts have been adduced to show that a freely-suspended needle in a state of oscillation is influenced by the magnetic force of the earth in a way analogous to that of a common pendulum oscillating by the influence of gravity; and that hence, by means of such a needle (138), we may determine the ratio of the intensity of terrestrial magnetic force throughout the whole extent of the earth's surface. This method of determining the magnetic intensity in the different regions of our globe was first suggested by Graham, so long since as the year 1775, and was afterwards more fully employed and perfected by Cou-

lombe, Humboldt, and Hanstein. The examination of the earth's magnetic intensity had also, at the instigation of the Royal Academy of Sciences, engaged the attention of the unfortunate La Perouse, in his expedition to the South Sea in 1785. The results, however, if any, perished with the expedition.

The nature and principle of the instrument more especially adapted as a magnetic pendulum has been already described and explained (139); and we have seen that the force urging the needle is taken as proportional to the square of the number of vibrations made in a given time. It is, however, essential to remember that, unlike the horizontal and inclined needles as to direction, this law applies as much to the magnetic force of the needle itself (141) as to the magnetic intensity of the earth, a condition which at once destroys the perfect analogy between a vibrating magnetic needle and a common pendulum, oscillating by the force of gravity. That would be the most perfect form of magnetic pendulum which would only involve in the consideration of the force in operation, the magnetic force of the earth itself, much in the same way as in measuring the force of gravity by the common pendulum we neglect the small attractive force of the matter of the pendulum, as being indefinitely small in comparison with the gravitating force of the earth. If a small needle of perfectly soft iron, not having any polarity of its own, and delicately suspended, could be caused to vibrate across the magnetic meridian at various parts of the earth, solely by the influence of terrestrial magnetic induction, we should then have a magnetic pendulum approaching the condition of the common pendulum; we cannot, however, produce such a result, and we therefore have recourse to needles of tempered steel, permanently magnetic; that is to say, we give our pendulum an inherent force, so as to put it in a position to operate upon the magnetism of the earth; it still remains, therefore, to inquire what new corrections it

may be requisite to introduce into our calculation of the experimental results obtained under this peculiar condition of the vibrating body, more especially when we observe (221), that the magnetic force exerted between opposite and permanent magnetic polarities, may vary in a different way, from that between a magnet and soft iron (218), and hence the same law of force between the centre and poles of a magnetic bar (227, Exp. 57), is not found to obtain when the force is taken between the different points of the bar and a small suspended magnet. The true measure of the earth's magnetic intensity at any point of its surface would be its inductive force on soft-iron. This, according to the laws we have arrived at (214), would be as the quantity of magnetism in operation directly, and as the distance inversely. Supposing we could actually measure the reciprocal force between any point of the earth's surface, considered as a magnet, and a given mass of soft iron, without sensible polarity, then, as we have shown (229 and 230), the relative quantity of magnetism in operation as referred to the earth, is represented by the square roots of the respective intensities or force of the reciprocal attraction.

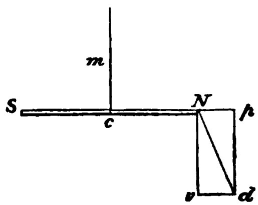
The method, however, commonly resorted to, of determining the magnetic intensity of any point of the terrestrial surface, is that of the vibrating magnetic bar (138) (254), as being upon the whole simple and available. It is, nevertheless, unquestionably open to objection, and the results hitherto arrived at by such means are not to be viewed in any other light than that of rough approximations. When we employ this method, we must take especial care to operate with the same needle, and with a needle in which the magnetism may be considered as invariable; to insure this, it is even found requisite to apply a small correction for changes of temperature.

255. In determining the terrestrial magnetic intensity with the needle of oscillation, we may either employ the

inclined needle (156), or the horizontal needle (142), or otherwise the vertical needle (156). From the circumstance, however, of the greater impediment to motion in the construction of the dipping-needle (153), the delicately-suspended horizontal needle (142) is commonly preferred; notwithstanding that it involves some final calculation before the total intensity can be determined.

Let, for example, S N, Fig. 125, be a light magnetic bar horizontally suspended by a fibre of silk *m* (142). Let N *d* be its natural inclination or dip at a certain point of the earth's surface; then taking this line N *d* to represent the total magnetic force,* we may conceive this force to be the equivalent or resultant of two other forces; one, N *p*, acting in the horizontal direction S N of the needle, and the other, N *v*, acting in the vertical or direction perpendicular to the line of the needle.* These two forces have been termed the horizontal and vertical components of the terrestrial magnetic force, such as it is found under any inclined or natural direction N *d*. If, therefore, we take the oscillations of the dipping-needle as a measure of the intensity, we may suppose the oscillations to result from the whole N *d* of the terrestrial magnetic force, since the needle vibrates across the line N *d*, or line of its natural direction; but if we take the oscillations of the horizontal needle as a measure of the intensity, then, as is evident, the vibrations do not result from the action of the whole of the terrestrial magnetic force N *d*, but only from that part of it, N *p*, acting in the horizontal line of the needle, and which will be greater or less according as the direction is more or less inclined to the horizon. Now it is easy to see in the above Fig. 125, that taking N *p* to represent the horizontal component of

Fig. 125.



* Rudimentary Mechanics. † See note (156).

the total force N d, we have N p = cos. of angle p N d (182); that is to say, the cosine of the dip. So that calling total force N d = R, and the horizontal force or component N $p = r$, we have r = R × cos. of dip, the cosine of the dip being the function of the obliquity which represents that portion of the whole force acting on the horizontal needle (196). We may arrive in a similar way at the total intensity by means of the vertical component N v, that is, by observing the oscillations of a vertical needle (156). In this case, however, we have to take into account the vertical force N $v = p\,d$ = sin. of the angle or dip p N d, which, calling the vertical force = S, gives S = R × sin. of the dip.* The first of these methods, however, is usually preferred; and from this we obtain $\text{R} = \dfrac{r}{\text{cos. of dip}}$.

256. We are indebted to the indefatigable Humboldt for the first practical results of the application of the needle of oscillation to the investigation of the variable magnetic intensity of the earth; having carefully determined the time of a given number of oscillations of a small magnetic needle at Paris, he transported the same needle to Peru, and again examined its rate of vibration; the result was, that whilst this needle performed at Paris 245 oscillations in ten minutes, it only made at Peru 211 oscillations in the same time. The relative intensities (139) therefore were as $245^2 : 211^2$, that is, as 1·3482 : 1; or, calling the intensity at Peru; a point of the magnetic equator; unity, then the force at Peru and Paris would be as 1 : 1·3482.† This kind of experiment has since been extended to almost every

* These formulæ will be more fully comprehended by referring to the notes in paragraphs 145, 183, and 196; see also p. 26.

† At the time when Humboldt made this experiment, an opinion prevailed that the intensity was the least where the dip was zero; it was on this account that Peru was taken as unity. Some doubts, however, have since arisen upon this point; still the scale assumed by Humboldt is usually resorted to; hence, to express intensities less than that of the magnetic equator, we must employ numbers less than unity.

known part of the globe; the result has been a series of numbers representing the ratio of the terrestrial magnetic intensity to a given unit for every point of the earth's surface. The following table may be taken as an illustration for a few remarkable places.

Place ..	A little W. of St. Hel.	Rio de Janeiro.	Cape of Good Hope.	Peru.	Isle of France.
Intensity	0·743	0·887	0·945	1	1·096

Place ..	Naples.	Paris.	Berlin.	London.	Baffin's Bay.
Intensity	1·274	1·348	1·350	1·369	1·707

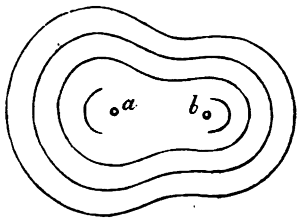
It appears by this table, as first announced by Humboldt, that the intensity is least about the equatorial regions of the globe, and greatest in the polar regions. By the indefatigable labours of Hanstein, Erman, and a few other observers, we are in possession of a table of intensities for a large portion of the terrestrial surface.

257. If we connect all those points in which the terrestrial magnetic intensity as thus deduced is the same, we arrive at a series of lines termed "Isodynamic," or lines of equal power. These lines, according to Sabine and others, are not always parallel to the isoclinal lines; the differences, moreover, are systematic. It has been further inferred, from a chart of these lines, that the points of greatest and least intensity are not identical with the points of greatest and least inclination; the intensity, therefore, of the magnetic equator may not be everywhere the same.

Although these isodynamic lines are still rough and incomplete, yet we cannot doubt of their being curves of double curvature returning into themselves. In Siberia and the Pacific toward the polar regions they are found, according to Hanstein and Erman, to consist of a system of double loops, as it were, enclosing two polar points. The

annexed Fig. 126 may be taken in the way of approximation to the form of these loops, in which *a b* are the points or poles of the system. Hanstein places the western of these intensity poles near Hudson's Bay, in lat. 50° N., lon. 90° W.; and the other eastern, or Siberian pole, in probably about 70° North latitude, and 120° East longitude. In the southern hemisphere, the loop form of the intensity lines and the two intensity poles are more fully developed as we recede from the equator. The two southern points have been placed, one to the south of New Holland, in lat. 60° South, lon. 140° East; the other, in the South Pacific Sea, also in lat. 60° South, but lon. 120° West. These four poles, therefore, are not diametrically opposite each other. The intensity of the North American pole and that of the southern pole, near New Holland, are nearly alike, being both about 1·8; as are also those of the Siberian and South Pacific poles, which are about 1·7. The two polar intensities, therefore, in each hemisphere, are of unequal force. Both the isoclinal and isodynamic lines would appear from these investigations to enclose two foci or points of greatest attraction, the bends or flexures of the curves being less marked as we approach the equator.

Fig. 126.



On comparing the observations of Sir James C. Ross with those of Erman, we find that the terrestrial magnetic force towards the south pole increases nearly in the ratio of 1 : 3. Since, upon a discussion of all the best observations, it appears that the maximum may be taken as 2·052, the minimum as 0·706; both these are found in the southern hemisphere. The ratio of the maximum to the minimum force then is as 1 : 2·9 nearly, or nearly as 1 : 3. From the profound inquiries of Gauss, it appears that the

total and absolute terrestrial magnetic force, considering the earth as a magnet, is equal to six magnetic steel bars of a pound weight, magnetized to saturation, for every cubic yard of surface. Compared with one such bar, the total magnetism of the earth is as 8,464,000,000,000,000,000 : 1, a most inconceivable proportion.

The terrestrial magnetic force as thus deduced by the needle of oscillation, like the elements of declination and dip, is subject both to secular and periodical changes (242). The amount of the secular change is not yet determined, according to Hanstein; however, the intensity is gradually declining throughout Europe. Sir James Clarke Ross, from observations on board the *Erebus* in 1839, concludes that the line of least intensity had advanced considerably northward.

The periodical and diurnal variation, as hitherto observed, gives a maximum of intensity between 9 and 10 P.M., and a minimum between 10 and 11 A.M. The monthly variation evinces a maximum in December and a minimum in June. The greatest change or difference in the annual intensity of the northern hemisphere is about 0·0359.

258. The needle of oscillation is not the only means employed for determining the magnetic intensity of the earth. Gauss resorts, for example, to a statical experiment, which consists in deflecting a magnet delicately suspended by a silk filament from its meridian, by means of a second magnet (134), and from which he conceives the absolute intensity may be derived.* Mr. Fox also proposes to determine the earth's intensity by means of weights applied on his dipping-needle deflector (160) to balance the dip.

Variations in intensity are measured by the bifilar and vertical force magnetometers (166) (168), as also by a species of steelyard balance contrived by Professor Lloyd.†

259. *Position of the Terrestrial Magnetic Poles.*—The

* See Gauss, Intensitas vis Magneticæ Terrestris, &c.

† Account of the Dublin Magnetic Observatory.

first step in the generalization of the phenomena of the declination of the magnetic needle is due to Halley, who conceived the notion of four terrestrial magnetic poles, two in each hemisphere, one fixed, the other in motion. The north pole, nearest to England, he places in lat. 83° North, longitude about 5° West of Greenwich; the other in lat. 75° North, lon. 115° West. The two southern poles he places, one in latitude about 74° South, lon. 95° West; the other in about 70° South lat., and lon. 120° East. These positions he thinks consistent with the then observed direction of the magnetic needle in various places. Churchman, in his "Magnetic Atlas," only traces two poles, one in lat. 58° North, lon. 134° West; the other in lat. 58° South, lon. 165° East. Hanstein, from his magnetic chart of variation, dip, and intensity (246), is led with Halley to infer the existence of two poles of unequal power in each hemisphere, toward which the isogonal lines appear to converge by two separate systems in each hemisphere. The stronger north pole he finds above the American continent, in lat. 70° North, lon. 92° West; the weaker he places in the Arctic Ocean, in lat. 85° North, lon. 140° E. The stronger south pole he places in lat. 69° South, lon. 132° E., not far south-west of Van Diemen's Land; the weaker south pole is in lat. 79° South, lon. 136° West, being south-west of Terra del Fuego. These four poles, therefore, are at present nearly diametrically opposite; their precise position, however, is subject to a great secular change. Did we infer the position of the magnetic poles from the course of the magnetic equator, considering them as the extremities of the axis of this great circle, we should find the north magnetic pole in Greenland, a little beyond Baffin's Bay, lat. 78°, lon. 60° West; and the south magnetic pole in the Antarctic Sea, lat. 76° South, lon. 130° East. The precise position and course of the magnetic equator, however, are still involved in doubt; which, together with the apparently uncertain and irregular distribution of the earth's magnetism, forbids our

placing any great confidence in the position of the two magnetic poles, as thus deduced.

By observations with the dipping-needle on board H.M. ship *Brazen*, in May, 1813, a point approaching verticity was found in Hudson's Bay, in lat. 69°, lon. 92° West. Parry, in August, 1819, was to the north of this, and found the dip 88° 37′. The position of the pole, from his subsequent observations, would be in about lat. 71°, lon. 93° West. In 1832, the observations of Sir James C. Ross completely confirmed the close approximative position of this point of polarity. This celebrated navigator found the dip near Prince Regent's Inlet, in the great American continent, lat. 70° North, lon. 96° West, to be within one minute of 90°, and which coincides wonderfully with Hanstein's deduction. Barlow also observes, "This is precisely the point in my globe and chart in which, by supposing all the lines to meet, the several curves would best preserve their unity of character as a system." So far, therefore, we have confirmed by observation the position of at least one point of verticity of the dipping-needle in the northern hemisphere. Gauss, whose enlarged, profound, and comprehensive views of terrestrial magnetism have so long commanded the attention of European science, has endeavoured, from certain theoretical considerations, to doubt the existence of more than a single pole in each hemisphere, one of which he places in about lat. 73° 35′ North, lon. 95° West; the other in about lat. 72° 30′ South, lon. 152° East. Both these points are not far from the results of observation.

Professor Barlow, following out his formula for the dip, viz., tangent $\delta = 2$ tangent λ (251), and, considering the magnetic condition of the earth as being analogous to that of a simple iron ball or shell (234), is led to conclude that each point of the terrestrial surface has its own particular polarizing axis, the extremities of which fall probably in all cases within the polar circles. These are the least limits we can at present assign them. There is consequently, he

says, no particular spot in the polar regions, which may, *par excellence*, be taken as the magnetic pole; if there were, he imagines it might, by the above formula, be easily computed, whereas, on subjecting the observed elements to calculations, he found discrepancies of no less than 10° of latitude, and 55° of longitude. Observation, however, still confirms the notion of a point of verticity for the dipping-needle.

260. *Magnetic Storms.*—Besides the secular and periodical variations of the magnetism of the earth, as indicated by the phenomena of the horizontal and inclined needles, we also find these needles subject to certain irregular variations, uncontrolled by any apparent law. It is to the illustrious and indefatigable Humboldt, that we owe all our first knowledge of such perturbations. Being engaged at Berlin in 1806 and 1807, in examining the changes in the declination of the needle for every half-hour, his attention was called to certain capricious agitations in its position, not referable to any accidental or mechanical cause, and which occasionally caused so great an oscillation as to lead him to refer them to a sort of magnetic reaction, propagated from the interior of the earth. He accordingly designates these disturbances as "magnetic storms," as being analogous to the sudden changes of electric tension which ensue in the electric storms of the atmosphere. During these storms the needle is observed to be affected by a sort of shivering motion, and to oscillate several degrees on each side of its mean position. In 1818, further observations were made simultaneously by Arago, at Paris, and Kupffer, at Kassan, in Russia, which showed, in a satisfactory way, that these perturbations, announced by Humboldt, occurred in both places at the same instant of time, notwithstanding that the places of observation were separated by 47° of longitude. Full attention being at length called to this subject, Humboldt, in 1830, succeeded in establishing magnetic observatories in various parts of Russia, which have since been extended to other

parts of the world (169), constituting such a network of inquiry into all the great facts of terrestrial magnetism as would have been but a few years before difficult to imagine. Since the year 1828, from Toronto, in Upper Canada, to the Cape of Good Hope and Van Diemen's Land, from Paris to Pekin, we find magnetic observatories, all established under one uniform system, and carrying on similar and simultaneous observations. The principal magnetic instruments employed in these observatories have been already described (162), and from continuous observations, carefully registered, in almost every country of the globe, we are presented with the startling fact of an unceasing series of what may be termed terrestrial magnetic pulsations, extending simultaneously over an interval equal at least to the whole breadth of Europe, and perhaps over the whole terrestrial surface. "When," says Humboldt, "the tranquil hourly motion of the needle is disturbed by a magnetic storm, the perturbation frequently proclaims itself over hundreds and thousands of miles simultaneously, or is propagated gradually in brief intervals of time in every direction over the surface of the earth."*

261. Beside these magnetic disturbances referable to some hidden and sudden change in the condition of the earth's magnetism, we find other singular disturbances in the position of the magnetic needle at the instant of the appearance of the Aurora Borealis, or Northern Lights. This fact was especially noticed and studied by Dalton so long since as the year 1793, who observed that the luminous beams were parallel to the dip, and the arches at right angles to the magnetic meridian. This disturbance of the magnetic needle consists in an irregular oscillation sometimes to the eastward, and then to the westward of its mean direction. The greatest amount of disturbance is when the Aurora is in the zenith. Hanstein also, who has studied this phenomenon, says that the shivering movements of the needle

* Cosmos.

never perhaps occur except at the time of an Aurora, and that the disturbances are felt at the same instant of time in places widely separated; the extent of the movement may, in twenty-four hours, amount to between 5° and 6°. This disturbance of the magnetic needle is equally wonderful and important in its character as the former, and may possibly be found to be identical with it. Arago thinks that the Aurora disturbs the needle even before the light shows itself in the horizon. The Auroras which are only visible in America and Siberia are, he says, found to affect the magnetic needle at Paris. It is not improbable that the presence of an Aurora and the disturbance of the magnetic needle are both effects of the same or a similar cause, so that we cannot assume the presence of the Aurora as the active force; we should rather regard it as an accompanying phenomenon; more especially as we find, according to Capt. Foster's observations at Port Bowen, that, during certain Auroras, the magnetic needle remains undisturbed. It has been further shown experimentally, by the author of this work (Edinb. Phil. Trans. 1834, vol. xiii.), that the magnetic oscillations are unaffected by the presence of a powerful column of mere electrical light flashing through an exhausted receiver 6 feet high and 4 inches in diameter.

Halley, more than a century since, considered the Aurora to be a magnetic phenomenon, a conjecture which bids fair to receive complete confirmation. According to Humboldt, the Aurora may be considered as a terrestrial magnetic activity raised to the intensity of a luminous phenomenon, one of the sides of which is the light, the other the disturbance of the needle; so that this magnificent appearance may be considered as the act of discharge at the conclusion of a magnetic storm.

VIII.

REVIEW OF MAGNETIC THEORY.

General Principles—First Views of Terrestrial Magnetism—Hypothesis of Halley—Speculations of Euler—Theoretical Speculations of Hanstein—Grover's Magnetic Orbit—Theory of Barlow—Hypothesis of Biot—Theory of Gauss—Electro-Magnetic Theory—Theoretical Views and recent Discoveries of Faraday—Theory of Ordinary Magnetic Action.

262. One of the great objects of physical science is to trace the relations and determine the laws of sequence in any observed series of natural phenomena, the study of nature being "the study of facts, not of causes;" it is this which characterizes the learning of the great founder of the inductive philosophy, and which essentially separates it from the conjectural philosophy of remote ages, the object of which was the study of causes rather than of facts. By the term theory, as applied in modern science, we are to understand an intelligibly connected body of facts, all referable to one or more general principles. With respect to the hidden or efficient cause of the phenomena observed, we have really no substantial knowledge of it whatever. That all bodies tend to the centre of the earth, and masses of matter toward each other, are universal facts, and upon these is based the whole theory of gravitation, and a lucid explanation of the system of the world. In the midst of this knowledge, however, we are most profoundly ignorant of the nature of the agency by which matter gravitates; and to speculate concerning it through the instrumentality of fiction, would be only to wander in a labyrinth of conjecture. What we call an explanation of observed phenomena, is a clear apprehension of all the dependencies in a great

chain of sequence. Take, for example, the question of the rise of water in a pump before the discovery of Toricelli; here we had two facts before us: the elevation of the fluid full thirty feet above its level, and the production of empty space by the motion of the piston of the pump, still the vacuum and the rise of the fluid had no apparent dependence on each other. The assumption by the ancient philosophers that the elevation of the fluid arose from the circumstance that nature abhorred a vacuum, was, in fact, no adequate intermediate link; it explained nothing. Directly, however, it was proved by the experiment of Toricelli that the atmosphere pressed upon bodies with a force equal to at least 14 lbs. on the square inch, then the cause of the rise of the fluid was instantly apparent, and the phenomena were explained. In the construction, therefore, of any theory, it is essential that the basis of it be some principle reducible to a fact; and, next, that the fact be universal; that is, without exception. Directly we refer the phenomena to any fictitious principle not reducible to a fact, we have no longer a theory; we have only at the best a conjectural hypothesis; in short, we substitute something which has no demonstrable existence for that which may be: in this case, we only require that what we assume is possible. An hypothesis of this kind is still not without its uses; and it is theoretically admissible so long as it runs parallel with the facts observed.

Magnetic theory, embarrassed by the complicated and mysterious character of the attendant phenomena, has hitherto made but comparatively little progress toward perfection; so that we are unable, as in gravitation, to refer the facts to one ultimate and universal elementary principle; hence almost every speculation relative to the phenomena of magnetism partakes more or less of the nature of an hypothetical assumption not based on any recognized fact.

263. *First Views of Terrestrial Magnetism.*—The philoso-

phers of the sixteenth century, not having any definite notion of the phenomena of the compass-needle, conceived it to be influenced by some mysterious point of force, existing in the regions of space. Descartes and others conceived it to be under the dominion of vast magnetic rocks. The discovery of the magnetic inclination (249) by Norman, in 1580, however, clearly proved that the cause of the directive position of the magnetic needle was to be sought for in the general mass of the earth; whilst Gilbert, in 1590, taking a bolder view of this great physical question, conceived the terrestrial sphere to be in itself a vast magnet, endowed with a permanent polarity, and hence approaching the general condition of an ordinary loadstone. Gilbert supposed, however, that the solid parts only of the earth were magnetic, not the water or other fluids; hence arose changes in the direction of the needle, which, whilst it assumed a given position, in obedience to the laws of common magnets (14), would at the same time be more or less drawn toward the land, and be influenced by it in various ways.

Bond, in 1673, endeavoured to calculate and explain the phenomena of the magnetic needle, on the hypothesis of the earth being a great magnet, and assumed the existence of two terrestrial magnetic poles, and a magnetic axis inclined to the axis of rotation, and passing through the centre of the earth; hence the magnetic poles and the true poles could not on this hypothesis coincide. With a view of explaining the great secular changes in the declination, the magnetic poles were supposed to have a slow movement of revolution about the poles of the earth.

264. *Hypothesis of Halley.*—It is to the celebrated Halley that we owe the first great attempt to bring the complex phenomena of the horizontal needle under the dominion of a more comprehensive theory, which, although it may appear at first to be of a somewhat rude and improbable character, still affords a fair field for the application of exact reasoning, and a means of comparing facts; indeed it

is but justice to this truly great man to observe, that he never pretended to more than an attempt to throw some light upon "the abstruse mystery of the variation," and lead philosophers to apply themselves more forcibly to so important a subject. Were the variation always relative to two fixed points or poles, near the poles of rotation, the magnetic axis passing through the centre of the earth; then it should be always the same for each place, and the lines of no variation would be meridian lines, passing through the magnetic and real poles of the earth; but the lines of no variation are not meridian lines, but curves of a somewhat inexplicable course (245). Halley, therefore, foreseeing this difficulty, assumed the existence of at least four poles, to which the variation had reference, two in the northern and two in the southern hemisphere; but since the observed phenomena evidently indicate a constant change of place in the relative position of these poles, he further supposes that the whole "magnetical system of the globe has one or perhaps more motions, the effects of which extend from pole to pole." To render this magnetical movement intelligible, he supposes a great portion of the interior of the earth to move within the external crust; and to admit of this motion, he imagines this interior portion to be detached and separated from the surface by an intervening fluid medium, so that, according to this, the terrestrial mass is a sort of double loadstone, consisting of an interior magnetic, spherical nucleus, surrounded by an external and spherical magnetic shell, the magnetic axis of each passing through the centre of the whole globe of the earth, the nucleus is supposed to have its centre of gravity fixed in the common centre of the general spherical mass, and to partake of the diurnal rotation about the same axis. By further supposing that the rotatory movement of the surface or external shell is rather more rapid than that of the interior globe, by some extremely small quantity, then, as is evident, the poles of the interior magnet will be continually shifting their places in respect

of the poles of the outer magnetic shell, being at every revolution left as it were a little in the rear, and consequently moving apparently westward. Halley supposes the difference of velocity to be so extremely little as to be scarcely appreciable upon 365 revolutions, and only to assume a sensible form by the operation of a great period of time. Under this condition, then, if we conceive the exterior shell to be a magnet, having its poles fixed, and at a given distance from the poles of rotation; and if the internal globe be also a magnet, having its poles fixed in two other places, distant also from the axis of rotation; and that these last poles are continually shifting their places in respect of the exterior poles, we may then, he thinks, give a reasonable account of the four magnetic poles of the earth, considered as a magnet, and the several phenomena of the variation of the horizontal needle. By the gradual translation of the poles of the internal globe, the direction of the needle is variously influenced, according to the directive power of each pole; hence there will be a period of revolution, after which the variations will return again as before. If they should not, then it may be inferred that there exist internal spherical shells, having a common nucleus, and consequently producing more magnetic poles, all these concentric magnetic spheres being separated by fluid media; and this he thinks a possible constitution of the interior of our planet, which, for anything we know to the contrary, may, through the operation of the fluid media, be a source of existence to organized beings. In this hypothesis all those parts of the earth nearest either of the poles will for the time be governed more or less by the influence of that pole; thus, taking the nearest pole to Britain as being in the meridian of the Land's End, and about 7° from the true north pole, this pole will govern Europe, Tartary, and the North Sea. All places to the east of this meridian will have a westerly variation; all places west of it a westerly variation, until we approach the influence of the other pole,

in North America, supposed to be on the meridian of California. The separate and combined influences of all the four poles in different zones of the earth produce the great differences observed in the variation of the needle.

This hypothesis of Halley, although far within the region of mere conjecture, and not at first view sanctioned by any high degree of probability, must still be considered as a valuable step in the progress of magnetic theory, and well calculated as a stepping-stone to more perfect views of the magnetism of the earth.

265. *Speculations of Euler.*—Euler, who investigated this subject in 1757, with his accustomed ability, does not think, in considering the earth as a magnet, that it is requisite to assume the existence of more than two magnetic poles, provided their just place be assigned. According to his view, we have yet to consider the case of two magnetic poles not precisely opposite each other, or, which comes to the same thing, in which the magnetic axis does not pass through the centre of the earth. Now, in this case, Euler endeavours to show that the lines of no declination may actually assume a direction similar to that which, from observation, we find they do assume; and that it is even possible to assign to the two poles such proportions as to produce lines of variation similar to those isogonal lines, which at first appear so unaccountable. Having fixed the two poles, the determination of the direction of these lines becomes a problem in geometry.

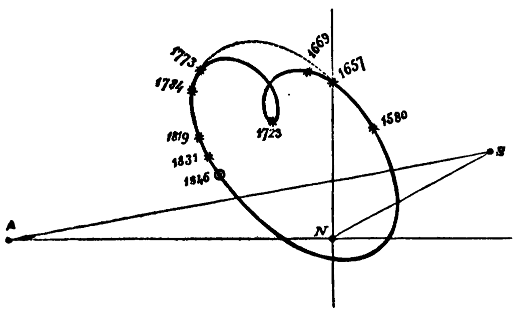
266. *Theory of Hanstein.*—Theoretical views of terrestrial magnetism do not appear to have greatly advanced beyond the condition in which Halley left them until 1811, when the Royal Danish Academy proposed the variation of the needle as a prize question; then it was that M. Hanstein undertook a re-examination of the whole subject, with a view to determine whether two magnetic poles, revolving round the pole of the earth in indefinite periods as maintained by Euler, would explain the phenomena; or whether four poles,

as assigned by Halley, were requisite; or, finally, whether the motion of magnetic polar points, about the poles of the earth, be in any way competent to represent the observed phenomena at all. We have already adverted to the extraordinary and elaborate magnetic charts of this unwearied philosopher, with their marked systems of isogonal lines, loops, ovals, and other intricate convolutions, and which it would seem are all sweeping westward, each in separate progression, and each assuming some new modification of flexure. So completely has the question been worked out, that by means of these charts we obtain a faint glimpse of the progressive state of magnetic declination for two centuries, viz. from 1600 to 1800. The results of the investigation confirm, according to Hanstein, the existence of four poles, as imagined by Halley. These four poles, however, are of unequal force, and are all supposed to be continually shifting their places; each has a separate independent movement and period. The present places of these poles, as assigned by Hanstein, we have already given (259); they are all supposed to have a regular oblique-circular motion about the poles of the earth,—the two north poles from West to East; the two south poles from East to West; and in the following periods:—The strongest north pole in 1,740 years; the weaker in 860 years: the strongest south pole in 4,609 years; the weaker in 1,304 years. Upon these data he assigns the position of these poles for the last half-century.*

* By a curious coincidence, these periods involve a number, 432, sacred with the Indians, Babylonians, Greeks, and Egyptians, as being dependent on great combinations of natural events; thus the periods 860, 1,304, 1,740, and 4,609, become by a slight modification 864, 1,296, 1,728, 4,320, which are not inadmissible, considering the complicated nature of the observations from which the first numbers are derived. Now these numbers are each equal to 432 multiplied by 2, 3, 4, and 10 successively. According to the Brahmin mythology, the world is divided into four periods, the first being 432,000 years, the second, 2 × 432,000, the third 3 × 432,000, the fourth, 10 × 432,000 years. It is also, according to Han-

267. *Grover's Magnetic Orbit.*—Much valuable information relative to this interesting speculation has been afforded by Grover.* By a careful and laborious examination of authentic observations, he endeavours to show that "the movement of the magnetic pole governing Europe is capable of recognition, that it possesses an orbitual character of which the general features can be distinctly traced." An horizontal action upon the needle is also inferred from these observations, depending on the isodynamic poles (257), by which he endeavours to explain the configuration of the isogonic lines. The magnetic orbit, as traced from observations on the magnetic needle in London, Paris, and St. Petersburgh, appears to be of the form given in the annexed Fig. 127. In this figure N is the true north pole in the

Fig. 127.



middle of a section of the northern hemisphere, and the

stein not unworthy of remark, that the sun's mean distance from the earth is 432 half radii of the sun; the moon's mean distance, 432 half radii of the moon; but what is more especially striking is the circumstance, that the number 25,920 = 432 × 60, is the smallest number, divisible at once by all the four periods, and hence the shortest time in which the four poles can accomplish a cycle. Now this time coincides exactly with the period in which the precessions of the equinoxes complete their circle, certainly a curious and remarkable series of coincidences.

* Observations on the Magnetic Orbit; by the Rev. H. Grover. London: J. Weale, 1850.

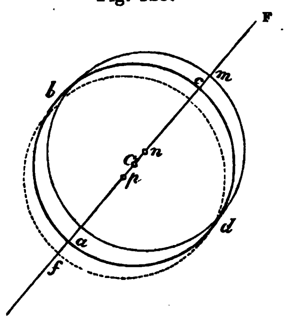
irregular elliptical curve, the path of the pole so far as hitherto observed. In this curve the author has localized eight assigned positions for the magnetic pole, from observations between the years 1580 and 1846. The points A and S represent the positions of the isodynamic poles, or points to which the isodynamic lines converge, one in Siberia, the other in America, and supposed to influence the position of the needle. In tracing the elements out of which this orbit is constructed, peculiarities present themselves, which throw much light on the whole magnetic system; for example, a certain acceleration and retardation of the motion, and the opposite bias of the two isodynamic hemispheres. By means of a critical examination of all the phenomena of this determined orbit, the author deduces some very general and curious facts bearing on the development of the magnetic lines, with their ovals, loops, and apparently inexplicable curvatures. The ovals he considers as temporary creations arising out of the peculiar position of the moving magnetic pole in relation to the two isodynamic poles A S, by which a bias is given to the needles of a whole district.

268. *Theory of Barlow.*—Professor Barlow, following up the construction of more perfect magnetic charts, is led to conclude that these charts present such a configuration of the magnetic lines as cannot be referred to any possible position of four or more magnetic poles; but conceives that each place has its own relative pole and polar revolution governed by some unkown cause. This theory is so general, that it must be conceived to set aside altogether the idea of any particular pole or point toward which the magnetic needle becomes directed, and consequently all idea of a single magnetic axis; it hence leaves the law of the changes in the direction of the needle undetermined. The fundamental principle, on which this theory rests, assumes the magnetic condition of the earth to be of that peculiar form observed in the passive or temporary magnetic state of a

soft iron ball or shell, and in which the poles or centres of action are always coincident with the centre of attraction of the surface, which is not the case in permanently-magnetized bodies. In these the centres of attraction are always at their poles. Professor Barlow having, as we have already seen (239), found the entire effect of a soft iron globe or shell to reside near the surface, proceeded to investigate a formula for representing the influence of these bodies on the compass-needle placed about them in different positions. Assuming upon the generally received hypothesis (14), that magnetic phenomena depend on two opposite fluids or forces, repulsive of themselves, but attractive of each other, and commonly existing in a greater or less degree of combination, we may suppose the action of the earth on spheres of soft iron, to take place on every particle of the mass in isoclinal lines (249) parallel to each other (102), and may further suppose that every particle of the iron is at the same distance from the centre of force as referred to the mass of the earth; in which case we may consider the effect upon each particle to be the same.

As this question is important in a theoretical view, we will take Professor Barlow's illustration of this probable magnetic condition of a soft iron ball or shell. Let *a b c d*, Fig. 128, be a neutral soft iron sphere; suppose F C *f* to be the direction of the dipping-needle, and F the centre of terrestrial magnetic force at an indefinite distance, then by the operation of this force upon each particle, in the way just stated, the two magnetic fluids or forces, resident in a combined state in the shell or globe *a b c d*, become separated, and may be supposed to form two spherical layers:

Fig. 128.



one $f\,b\,d$, whose centre is p; and another $m\,b\,d$, whose centre is n; the distance of these centres $p\,n$ from each other depending on the susceptibility of the iron and other contingencies. In computing the action of an iron sphere in this state upon a distant magnetic particle, we may refer the action to those two centres $p\,n$, according to any assumed law of force (175). Professor Barlow supposes the force to be in the inverse duplicate ratio of the distance. This view differs from others of a similar kind in this, that the action or displacement of the fluids is referred to each particle, instead of the fluids being separated and accumulated in distinct poles; and also in the great fact that the displacement is confined to the surface, and not, as Coulombe supposed, referable to the mass. The centres of action $p\,n$, therefore, may become indefinitely near each other in the common centre of attraction of the surface, which is coincident with the centre of attraction of the mass only in spherical bodies, but on no others. Now by referring the earth's magnetism to an existing magnetic condition such as this, Professor Barlow finds that he is enabled to apply the analytical expressions, he had previously deduced for representing the influence of an iron sphere on the compass (238), to the phenomena of terrestrial magnetism; his general deductions being that the earth is not a permanent magnet, but owes its magnetic state entirely to induction; and that its action may be referred to two poles indefinitely near each other in the common centre of attraction of the surface; that is also of the mass of the earth. The latent magnetism of the sphere has in this case a mere condition of polarity. From whence this induction proceeds he does not pretend to determine. The illustrious Gableo had an idea that a magnetic agency existed in some points of space, which led him to ascribe the parallel direction of the earth's axis to a magnetic point of attraction in the distant heavens.

269. *Hypothesis of Biot.*—Biot, so long since as the year

1805, not finding it possible to reconcile observations on the variation and dip of the needle with the existence of two poles or centres of force near the terrestrial surface, thought of treating this problem under the condition that those centres were indeterminate, and then by a comparison of the general analytical result with further observations, endeavour to arrive at the precise position of these poles. Now it is not unworthy of remark, as being very confirmatory of Barlow's views, that the nearer the poles were taken toward each other, the nearer the computed and observed results were found to agree; until, at length, by taking them indefinitely near each other in the centre of the earth, the computed and observed results in many cases completely coincided. In this investigation Mons. Biot assumes two points in a given terrestrial magnetic axis, by one of which the needle is attracted, by the other repelled; and then investigates a formula for representing the dip and declination of the magnetic needle in any part of the earth in terms of an indeterminate distance between these points.

270. *Theory of Gauss.*—This accomplished philosopher, whose magnetic researches have become in recent periods the wonder and admiration of Europe, assumes the terrestrial magnetic force to be the collective effect of the magnetism of the mass, and is led to consider the term pole as a very arbitrary assumption; no number of definite points, be they 2 or 4, or even more, will explain the phenomena according to the laws of common magnetism. In the most simple meaning of the term pole, Gauss considers that there are only two, one in each hemisphere. If there were four, we should have necessarily three points of verticity in each hemisphere; that is to say, there would be a point between each two poles in which the needle would not obey the action of either exclusively, and would, consequently, be vertical; but such is not found to be the case. Gauss, starting from a great general principle, that mag-

netism is distributed through the mass of the earth in an unknown manner, has succeeded in obtaining, partly by theory and partly by adaptation, a sort of empirical formula which represents in a wonderful way the many complicated phenomena of the magnetic lines, and has so far embodied our knowledge of these phenomena in a law mathematically expressed. Gauss's investigation depends on the development of a peculiar function much employed in Physical Astronomy, and which is obtained by summing all the attractive and repulsive elements, each molecule being divided by its distance from the attracting or repelling point; what are termed the differential coefficients of this function express the resolved components of the total magnetic action (255). By this process it is demonstrated that whatever be the law of magnetic distribution, the dip, horizontal direction, and intensity at any place on the earth may be computed. Having exhibited his resulting formula in converging series, Gauss determines the declination, inclination, and intensity for ninety-one places on the earth's surface, and which are found to coincide with observation: one great feature, therefore, in this theory of terrestrial magnetism is, that the earth does not contain a single definite magnet, but irregularly-diffused magnetic elements, having collectively a distant resemblance to the condition of a common magnet. So that for magnetic poles we must substitute magnetic regions, over which a general magnetic influence obtains. Thus, instead of a Siberian pole, as determined by Hanstein, we have a Siberian region, in which the isogonal lines may be conceived to converge without coming absolutely to a point.

271. *Electro-Magnetic Theory.*—The solution of the problem, from whence the mass of the earth derives its magnetic state, is not in any way approached with so high a degree of probability as by the theory of electro-magnetic currents, caused to traverse the earth's surface by some of those natural agencies so continually operating on it. We

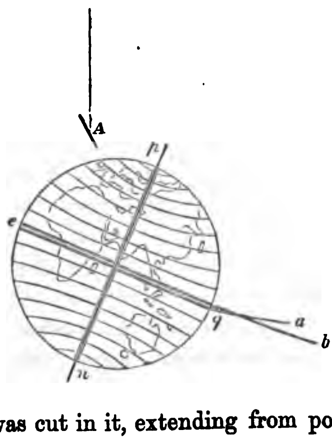
have seen (68), that by heating one extremity of a metallic bar or rod, the opposite extremity being kept cool, so as to produce a disturbed equilibrium of temperature, electro-magnetic currents are produced, of such force as to turn the compass needle at a large angle to its meridian. Sir David Brewster, so long since as the year 1821, observed a remarkable coincidence between the isothermal lines, or lines of equal heat, laid down by Humboldt, and the isogonal lines of Halley, and had deduced for our northern hemisphere two poles of greatest cold, both in the locality of Hanstein's magnetic poles, viz., an American pole, lat. 73° North, lon. 102° West; and an Asiatic pole, lat. 73° North, and lon. 78° East. Sir David Brewster* is led to conclude that two meridians of greatest heat, and two of greatest cold, are called into play, and was finally led to imagine that the magnetism of our globe depended in great measure on electro-, or rather thermo-magnetic currents. Taking into consideration the heated belt of the equatorial regions, and the mass of the polar ices on either side of it, we have, as observed by Dr. Traill, all the conditions of a vast thermo-magnetic machine. A great link in the chain, however, is still wanting; it is very difficult to say how or in what way these currents are caused to circulate about the mass of the earth. Grover, in his interesting little work on the magnetic orbit, already alluded to, has some interesting observations on this question. According to his view, the atmosphere is the immediate source of terrestrial magnetism, which contains within it isolated columns of conducting media; these surround the earth, and in such way, that in 365 revolutions the sun generates in it an electro-magnetic circulation; thus the terrestrial surface becomes enveloped in a vast electro-magnetic spiral coil (51), and we who live on it become placed intermediate between the coil and the surface by those peculiar motions of the earth which arise from the yearly cycle finding its period at different hours of the day,

* Edin. Phil. Trans. vol. ix.

and on different meridians; such a change may take place in the precise position of this great atmospheric coil from time to time as would correspond with the orbit of the magnetic revolution (267). The phenomena of periodical variations depend evidently on the action of heat and the position of the sun, and probably on resulting thermo-magnetic currents. Beyond this mere assumption, however, we have not any very secure basis for reasoning; the most admissible view of this kind of action, however, is the following:—During the diurnal motion of the earth, its surface, especially about the tropics, is continually heated and cooled in successive points, and in an east and west direction: if we admit, as in Exp. 50 (68), that thermo-magnetic currents become from this cause excited, and circulate in an east and west direction over the terrestrial surface, the result will be a magnetic development in direction north and south (48); hence there will be a magnetic development in the earth in a direction nearly parallel with its axis.

272. *Barlow's Electro-Magnetic Globe.*—From no one has the preceding electro-magnetic theory received so much substantial and fine experimental support as from the profound and great philosophical ingenuity of Professor Barlow. A hollow globe of wood, *p n*, Fig. 129, sixteen inches in diameter, had a groove, *e q*, cut round its equatorial part, to represent the equator, and also other grooves, in parallels of latitude distant 4½° from each other. A deeper and wider groove, also, *p n*, was cut in it, extending from pole to pole in the line of a

Fig. 129.



single meridian. Things being thus arranged, the middle portion of a copper wire $\frac{1}{10}$ of an inch in diameter, and ninety feet long, was applied to the equatorial groove, in a point opposite the line of the meridian *p n*, which, being bent each way, in the equator *e q*, to meet at the groove *p n*, was continued toward each pole by a continual coiling and turning into the parallels of latitude. Finally, the remaining portions of the wire were covered with insulating varnished silk thread, and passed through the meridian groove toward the equator, and the two extremities, *a*, *b*, brought out for connection with the poles of a voltaic combination (40) (47). The whole was now covered with the pictured gores of a common globe, and in such way as to bring the poles of the electro-magnetic spiral as nearly as possible into the position of the observed terrestrial magnetic poles, viz., lat. 72° North, and lat. 73° South, and on the meridian corresponding with lon. 76° West of Greenwich.

The globe being now conveniently placed under a delicately-suspended needle A, Fig. 129, carefully neutralized in respect of the earth's action (164), electro-magnetic currents were caused to circulate through the spiral beneath the paper surface (40). When the globe was so placed as to bring London into the zenith, the suspended needle took the inclination of the dip, at that time 70°, and also the line of the variation, at that time about 24° West. On turning the globe round so as to bring other places of the same parallel under the needle A, the dip of 70° remained, but the line of declination changed its direction, becoming first zero and then increasing eastward, much in the same way as happens in the case of the horizontal needle. When the globe was turned so as to cause the pole to approach the zenith, the dip increased up to a point of verticity; and on turning it so as to bring the equator into the zenith, the suspended needle became horizontal. Continuing the motion so as to bring the south pole

toward the zenith, the suspended needle inclined in the opposite way, thus representing on a small scale all the phenomena of the horizontal and inclined needles. Professor Barlow thinks that he has proved the existence of a force competent to produce all the phenomena of terrestrial magnetism, without the aid of any body commonly called magnetic.

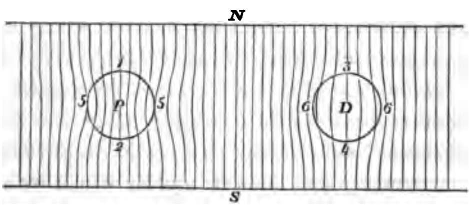
273. *Theory and recent Discoveries of Faraday.*—This distinguished philosopher, with his accustomed vigour of intellect and practised experimental hand, has not left the question of terrestrial magnetism unassisted by his immense labours. The general views which he is led to entertain upon points connected with the earth's magnetism may be thus stated:—Space devoid of matter, as also material space, that is, space in which matter is found, may be taken as being traversed by lines of force, operating, as it were, immediately through it. The condition of the space intercepted between the iron walls of the magnetic field, Fig. 59 (74), and Fig. 58 (72), may be taken as illustrative of this assumed physical condition of things. Now, although it may appear to many persons very difficult to conceive the existence of mere force independent of what we commonly call matter, yet we must recollect that, both in Electricity and Magnetism, it is with forces that we are principally concerned; and that, after all, it is far more difficult to conceive the existence of matter without properties of this kind than such properties without the matter; in fact, we recognize forces almost everywhere; but we recognize nowhere the ultimate atom of solidity of which matter is supposed to consist. All space, either vacant or occupied, presents for our consideration forces of various kinds, and the lines in which these forces are exerted. In viewing different substances in relation to lines of magnetic force, it is found that some bodies assume a position perpendicular to the direction of these lines; that is, they take an equatorial direction (74); others coincide in direction with the lines

of force, and take an axial direction (76). Pure space, devoid of matter, is conceived to have a magnetic relation of its own; that is to say, it permits lines of force to traverse it without in any way affecting them. The introduction of certain kinds of matter into space so occupied by force, will, on the contrary, change the existing state of the lines by either increasing or decreasing the facility of transmission. Common matter, when referred to lines of magnetic force traversing pure space, may be considered as being either zero, or as producing no change, or as being on one side or the other of zero; that is, as producing opposite effects. Hence has arisen a classification of two kinds of magnetic substances, viz.:—Those which point axially (76), and which have been termed Paramagnetic substances, and those which point equatorially, termed Diamagnetic. So that, taking the term "Magnetic" in its most general sense, as applicable to all the phenomena, we have the following division:—

$$\text{Magnetic}\begin{cases}\text{Paramagnetic.}\\ \text{Diamagnetic.}\end{cases}$$

When Paramagnetic or Diamagnetic substances are introduced into the magnetic field, they either increase or decrease the degree in which the force is transmitted, and thus disturb the uniformity of the lines. Paramagnetic substances, for example, concentrate the lines of force upon themselves, as represented by P in the annexed Fig. 130. Diamagnetic bodies, on the contrary, expand the lines of force, and cause

Fig. 130.



them to open outward from themselves, as represented by D in Fig. 130. Faraday calls this, for the moment, magnetic conduction. Paramagnetic bodies, when introduced into the magnetic field, always tend, from their power of concentration of force, from weaker to stronger places of magnetic action, and are urged in the axial line (76). Diamagnetic bodies, on the contrary, tend from stronger to weaker places, and are repulsed to the equatorial line (74). The force which thus urges bodies to the axial or equatorial lines is not a central force (179), but a force differing in character in the axial or radial directions. One may retain a very concise notion of this paramagnetic and diamagnetic relation, by conceiving that if a liquid paramagnetic body were introduced into the field of force, it would become prolonged axially, and form a prolate spheriod; whilst a liquid diamagnetic body would become prolonged equatorially, and form an oblate spheriod.

274. *Atmospheric Magnetism.*—By one of those happy trains of thought peculiar to great philosophical minds, Faraday conceived the idea of an atmospheric magnetism, and succeeded in proving that gaseous substances, when in the magnetic field, obeyed the same laws as all other matter. Thus oxygen gas, enclosed in a thin envelope, becomes drawn paramagnetically into the axial line, and is hence attracted by the magnet after the manner of iron (80), whilst olefiant gas, for example, is repelled diamagnetically into the equatorial line after the manner of bismuth. The nitrogen of the air does not appear to be either paramagnetic or diamagnetic, but to consitute the zero place in the scale of different substances. In thus demonstrating the paramagnetic property of oxygen, we arrive at the very important fact, that two-ninths of the atmosphere, by weight, consists of a substance, magnetic in character, after the manner of iron, a substance liable to vast changes in its physical conditions of temperature and density, and by which its magnetic character would be liable to vary, independently of all

consideration of magnetic force existing in the mass of our globe, considered as a magnetic body *per se*.

The earth itself may be considered as a spherical mass, consisting of both paramagnetic and diamagnetic substances very irregularly disposed; it is nevertheless to be considered on the whole as a magnet, and as an original source of power. The magnetic force of this great system is disposed with a certain degree of regularity, so far as our opportunities of examining it extend, which is only on its surface. The lines of force which pass in or across this surface are made known to us, as respects direction and intensity, by means of small standard magnets. The average course, however, of these lines and their temporary variations, either in the space above or in the earth beneath, are but very obscurely indicated through the same means. Our observations, in fact, do not tell us whether the cause of the variations is above or below.

The lines of magnetic force issue from the earth in the northern and southern parts, with different but corresponding degrees of inclination, and incline to and coalesce with each other over the equatorial parts (28).

The lines of force which proceed from the earth into space most probably return to it again; but in their circuitous course may extend to a distance of many of its diameters, to tens of thousands of miles. Space then forms the great abyss into which such lines of force as we recognize by our instruments proceed. Between the earth and this space, however, there is the atmosphere; it is at the bottom of this we live, and in the substance of which we carry on all our inquiries. Now this medium is, as we have just seen, highly paramagnetic, and may evidently become changed in its magnetic relations by any change incidental to temperature or pressure. None of these changes can happen without affecting the magnetic force emanating from the earth, and causing variations at its surface both in intensity and direction.

Having examined a variety of circumstances affecting the magnetic condition of the atmosphere, and the probable way in which such changes would affect the magnetic needle, Faraday concludes that the magnet, as at present applied, is not always a perfect measure of the earth's magnetic force. The intensity (254), for example, in oxygen, of a given density, would be different from those in expanded oxygen, although the same amount of lines of force and magnetic energy were present in both cases. To understand this, we have to consider that a needle vibrates by gathering upon itself the lines of force P, Fig. 130, and which otherwise would traverse the space about it. If the oxygen, therefore, be made dense, and a better conductor; then the magnet would carry on less of the force, and the oxygen more; it is therefore very important to know whether, when the magnet indicates an increased intensity; the intensity is due to the earth as a source of power, or to a change in the magnetic constitution of the surrounding space.* Considering that the magnetic state of the earth may not change whilst the oscillating needle, by the influence of the different conditions of day and night, or of summer and winter, may show a difference; so far the magnet, as at present applied, is not, according to this theory, a perfect measure of the terrestrial magnetic intensity. It is to the magnetic constitution and condition of the atmosphere, and the changes liable to be effected in it from changes in temperature, pressure, &c., that Faraday refers the annual and diurnal variation of the needle, and other periodical changes to which it is subject. Thus the position of the sun at a given place affects the atmosphere; the atmosphere affects the direction of the lines of force: the lines of force there affect those at any distance, and those affect the needles which they respectively govern. The sole action of the atmosphere is to bend the

* The author of this work first pointed out the necessity of placing the oscillating magnet in a space as nearly approaching a vacuum as possible. —Edinb. Phil. Trans. for 1836, vol. xiii. part 1.

lines of force, whilst the needle, being held by these lines, changes in position with the change of the lines. The needle is in fact a sort of balance, on which all the magnetic power around a given place hangs. Its mean position is the normal position. The fixation of the lines of force on the earth brings the needle back from its disturbed to this normal state; thus, as the earth rolls on in its annual course, that which at one time was the cooler becomes the warmer hemisphere, and in its turn sinks as far below the average magnetic intensity as it before stood above it. Now, since the sum of the forces passing out from the earth wherever there is dip, must correspond on each side of the magnetic equator, it is impossible that they should become more intense in one hemisphere or more feeble in the other, without corresponding effects upon the position of the magnetic equator itself, which may be thus expected to undulate, as it were, with the force, and move alternately north and south every year.

In the case of the diurnal variation, the whole portion of the atmosphere exposed to the sun, receives power to refract the lines of force, and the whole of that which covers the darker hemisphere assumes an equally altered but contrary state. It is as if the earth were enclosed within two enormous magnetic lenses, competent to affect the direction of the lines of force passing through them.

This hypothesis does not assume that the heated or cooled air has become actually magnetic, but is changed only in its power of transmitting the lines of magnetic force. It does not at present profess to apply to the magnetic or great secular changes of terrestrial magnetism, or to the cause of the magnetic state of the earth itself. With respect to variations of magnetic force not periodic but irregular (260), Faraday refers them to varying pressure, winds, currents, precipitations of rain or snow, &c., all of which may change the magnetic conduction of the air; and in this way the presence of a mere cloud near a station may do more than

the rising sun. Where the air is changed in temperature or volume, there it acts and there it alters the directions of the lines of force, and these by their tension carry on the effect to more distant lines, whose needles thus become affected also.

275. *Theoretical Review of Ordinary Magnetic Action.*— The first idea of ordinary magnetic phenomena was, as we have seen (13), the doctrine of Thales, who conceived the magnet to possess a species of animation; this doctrine, however, was superseded by the doctrine of magnetic effluvia (13), a principle which engaged the attention of philosophers down to the time of the celebrated Boyle. Lucretius, in his fine poem "De Rerum Naturâ," supposes that in the attraction of iron the effluvium of the lodestone displaced the surrounding air, in consequence of which atoms of iron flew toward the void, and in doing so dragged the iron toward the lodestone. Following this hypothesis arose the notion of an expansion and contraction of the effluvia, which being thrown outward from the magnet, seized upon ferruginous matter, and drew it by a collapse to the magnetic pole. Boyle resolves magnetic effluvia into indefinitely small atoms of magnetic iron, so indefinitely small as to permeate solid substances, and thus the lodestone is enabled to seize upon iron so forcibly as to raise it against its own gravity.* Gilbert imagines magnetic force to depend on what he calls "a formal efficiency," a "form of primary globes," of which forms there is one in the sun, one in the earth, another in the moon. Magnetism is the "formal efficiency" peculiar to the earth. The views of this truly great philosopher are, it must be allowed, very obscurely expressed, and, in common with all the preceding, were never practically applied in physico-mathematical science.

276. Des Cartes, casting aside all preceding doctrines, applied his famous system of vortices of ætherial fluid in explanation of magnetic action. The Cartesian hypothesis

* Essays on Effluviums, p. 33. London, 1673.

supposes matter to be indefinitely extensible without any other property, and to consist of atoms of different forms —every other quality being derived from ætherial elastic fluid continually revolving in vortices or eddies of various orders. The magnetic curves (28) he thinks an evidence of this. In no instance has the reasoning of this distinguished man been so persuasive as in the application of his theory to the phenomena of Magnetism.

277. Dr. Gowen Knight supposes magnetic action to depend on the circulation of a repellent fluid existing in space and in the pores of steel,* and capable of passing in and out of the magnet, or between magnetic poles, in one direction only. This hypothesis he thinks consistent with the observed phenomena. If, he says, a reason can be assigned for this circulation, then the "whole mystery of magnetism is solved." Attraction, upon this hypothesis, is the result of the fluid circulating from the pole of one magnet to the pole of another, Fig. 17 (28). Repulsion, on the contrary, is the result of opposed streams, Fig. 18 (28). Dr. Knight's work is by no means undeserving of notice, as being one of the first attempts to account for magnetic phenomena through the mechanics of matter and motion; and although strong exceptions have been taken to his postulates, the question how far they lead us to conclusions in accordance with observation still remains to be considered; of the agents employed by nature we really know nothing, except by the assimilation of effects with other agencies familiar to us. One of the great objections taken to this hypothesis is, that it is irreconcilable with the particular law of force deduced by Lambert and Coulombe, and should therefore be discarded.† This is, however, a somewhat hasty conclusion, since we have already seen, both experimentally (209) and by the researches of Faraday (274), that Magnetism is not necessarily a central force,

* Attempt to explain the Phenomena of Nature, &c. London, 1748.

† Library of Useful Knowledge. Magnetism, p. 33.

and that the law deduced by Coulombe and other philosophers is only a particular case of a more general form of magnetic action (215).

278. It is not unworthy of remark, that soon after the discovery of Electro-magnetism in 1819, Ampere developed his beautiful Electro-dynamic theory, and showed the mutual attractions and repulsions of electrical currents* according to a certain fundamental law; by assuming for a magnet a peculiar structure, he brings it under the dominion of this law, and by a most beautiful experiment shows that the circulation of electrical currents in a spiral wire, Fig. 43 (51), imparts to that wire all the properties of polarity in the direction of its length; and is finally led to conclude that a magnet has a current of electric fluid circulating about it in planes nearly perpendicular to its axis.

279. Following Dr. Knight's work, we have the fine work of Æpinus,† in which the author supposes the existence of an ætherial fluid, termed the magnetic fluid, the particles of which repulse each other, but attract, and are attracted by the particles of ferruginous matter. He further supposes that, in the absence of this magnetic fluid, the particles of ferruginous bodies also repulse each other, but attract the magnetic fluid; all these attractions and repulsions conform to the general law of central forces, being as the squares of the distances inversely. Æpinus had the great merit of reducing the laws of equilibrium of such a fluid and common matter to strict mathematical investigation, and of affording, in a great majority of cases, a satisfactory explanation of the phenomena. According to the hypothesis of Æpinus, the condition of a magnet is an induced disturbance of the magnetic fluid it contains, from which results a redundancy or accumulation of fluid in one pole, and a deficiency, or what may be termed redundant matter, in the other. This

* Rudimentary Electricity, second edition, p. 170.

† Tentamen Theoriæ Electricitatis et Magnetismi.

positive and this negative pole attract each other because of the mutual attraction between the redundant fluid of the positive pole and the redundant matter of the negative pole. Two positive poles repulse each other from the mutual repulsion of the particles of the magnetic fluid; two negative poles also repulse each other in consequence of the repulsion of the particles of redundant matter. Induction is the result of similar attractions and repulsions upon the magnetic fluid and ferruginous matter or distant iron by an overcharged or undercharged pole.

280. The French philosophers, startled at the assumption of a repulsive force in the particles of common matter, as being contrary to a fundamental law of gravity, changed the terms of the hypothesis of Æpinus, without altering virtually its application. Having assumed the existence of a primary magnetic fluid, they supposed it be a compound of two elementary principles, an austral and a boreal fluid, each repulsive of their own particles, but attractive of each other. Magnetic action is the result of a separation of these elementary fluids in each particle of the mass, and to which they are confined. This hypothesis originated with Coulombe about the year 1780, after the discovery of the opposite electricities, and the electrical theories of Du Fay and Symmer. It has since been more especially carried out in all its generality by M. Poisson, in his elaborate and mathematical analysis of the phenomena of Magnetism. M. Poisson proves that the sum of the actions of the magnetic elements in a given magnet are the same as if they proceeded from a thin stratum of each fluid occupying the surface only, and so distributed that their total action upon the interior of the body is equal to zero. We have only to substitute the term austral fluid for redundant matter or deficient fluid, and we have nearly the same result. Bonnycastle, in his application of this hypothesis, conceives the two fluids to have accumulated in opposite parts of a

magnet, which would make it identical with the hypothesis of Æpinus, by only changing the terms; whilst Barlow, as we have seen (264), confines the action to the surface of the magnet altogether, and refers the respective centres of force to two centres indefinitely near each other in the centre of attraction of the surface.

We have rather dwelt on these views of Æpinus and the French philosophers because of their admitting of the application of strict mathematical reasoning, and because of their being generally received as adequate to the explanation of magnetic action, no other equally substantive theories having been hitherto proposed; we must not, however, imagine that either of these hypotheses furnishes a real explanation of magnetic force, or that the existence of a magnetic fluid or fluids is, after all, anything more than a fiction of the mind, employed as a temporary substitute for truth. Still they greatly assist us in arriving at what we may consider as a true theory, viz., a resolving of classified facts into other facts still more general, and the final development of one great ultimate fact common to them all. Few who have considered the more recent progress of Electricity and Magnetism, more especially the brilliant researches of Faraday, will be disposed to place much confidence in the notion of electrical and magnetic fluids, and who will not perceive that the phenomena depend in all probability upon a principle of causation of a very different character. Grove, reasoning on the correlation of physical forces, considers Magnetism as a mode of motion caused by certain undulations or vibrations in the particles of common matter. Faraday, as we have seen,* disencumbers himself of the common theory of material atoms, and refers the phenomena to certain lines of force traversing space (273), and the relations which various substances have to these

* Rudimentary Electricity.

lines. In all these speculations the student will do well to remember that it is quite in vain to seek for an adequate explanation of causation in the abstract; all we can hope to arrive at is, as just observed, the resolving of phenomena into an intelligible sequence, and showing their dependence on some great ultimate principle reducible to a fact. This it is which constitutes a perfect theory.

IX.

THE MARINER'S COMPASS.

Early History—The Mariner's Needle—Dr. G. Knight's Inquiries—Best Form and Conditions of Compass Bars—Modes of Suspension—Scoresby's Compound Bars—Employment of more than one Needle in the same Compass; various kinds of Sea-Compass—Committee of Inquiry into the State of the Compass Department of the Navy—The Admiralty Compass—Application of Magneto-Electrical Action to the Movements of the Needle and Compass by the Author—Magnetic Observatory at Woolwich—Mode of testing the Compasses of the Royal Navy—Local Attraction of Ships—Iron Ships—Deviations of the Compass on Shipboard—Methods of Correction.

281. We have already described (148) in a general way the nature and use of the mariner's compass, and have further explained (243) the terrestrial magnetic variations to which it is subject; there remain, however, to be yet considered some other circumstances connected with this superb invention demanding especial attention; these relate principally to certain improvements in the construction and use of the compass, and the deviations to which it is liable in consequence of the local attraction of a ship, especially of an iron ship, together with the methods hitherto practised for determining and correcting such deviations. Upon a review of the immense importance of this subject, therefore, as a branch of Magnetism, we have thought it desirable to devote a few pages to the exclusive consideration of this wonderful instrument, which, taking it in all its generality, may be considered as the polar star of magnetic science.

282. The application of the directive property of the lodestone (6) to the purposes of perilous journeys on land, and to the art of navigation, may be considered, probably,

the first, as it was certainly the greatest practical use to which Magnetism has been as yet made subservient, and furnishes an invaluable lesson in attempts to investigate nature by a careful collection of facts, however trifling the facts may appear. The person who first observed the attraction of one particle of iron toward another, little thought of its leading to a means of guiding the mariner over a perilous and pathless ocean in the midst of darkness and tempest, without any other light to cheer his way than that of a small lamp shining on a piece of steel; yet such has been the result of the discovery of magnetic agency. By whom the mariner's compass was first invented, or with what nation it may have originated, has never been circumstantially determined; it is, however, pretty certain, as observed by the indefatigable Humboldt, that, at least seven hundred years before it was employed by European nations, Chinese craft were sailing on the Indian Ocean under the supposed guidance of south magnetic indication: this, together with the proved use of the common compass in China from the earliest times of which we have any record, the terms the Chinese employ to designate it, and the prevailing idea in that country that the needle points south, go far in corroborating the opinion that the mariner's compass originated in China, or in some part of India (8). A rude form of compass is said to have been invented in upper Asia, and from thence conveyed by the Tartars to China.*

The employment of the needle in navigation appears to have been first generally introduced into Europe towards the end of the thirteenth, or the beginning of the fourteenth century, and is attributed to a Neapolitan, a noble citizen of a town of Principato, which has ever since borne the figure of a mariner's compass as the arms of the territory.

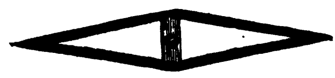
283. The magnet, when first used in navigation, consisted of a common sewing-needle, which, being rendered magnetic,

* Mrs. Somerville, Physical Sciences, p. 338.

was passed through a piece of reed or cork, sometimes forming a cross, and allowed to float on the surface of water; hence, probably, the term "magnetic needle." Such, at least, was the practice of the captains navigating the Syrian seas in 1242.* Subsequently, however, the needle was increased to about six inches in length, and suspended on a point, in a white china dish filled with water, probably to prevent it from falling toward the side of the vessel. The present form of the mariner's compass (148) is undoubtedly of comparatively recent date, and it is equally certain that advances toward refinement in its construction have been very slow; indeed, so lately as the year 1820, Professor Barlow, who was directed by the Board of Admiralty to investigate and report on the state of the compasses furnished to the royal navy, states, "that at least one-half of them were mere lumber, and ought to be destroyed." Flinders also observes, "the compasses of the royal navy are the worst-constructed instruments of any carried to sea."

284. We are indebted to Dr. Gowan Knight † for many valuable attempts to improve the mariner's compass in this country. Almost all the needles in merchant ships were, at the time he wrote, in 1750, composed of two pieces of steel, bent in the middle, and united in the form of a lozenge or rhombus, as in the annexed Fig. 131. This form he considers as very objectionable. Having examined twenty of these needles, he found them all to vary from the true direction. Should the temper of the steel be unequal, the hardest sides will have, he says, the greatest directive power. Besides this, the sides which nearest agree in direction with the earth's magnetism, when the needle deviates from the meridian, will tend to preserve the decli-

Fig. 131.

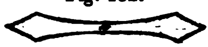


* Klaproth, Lettre à M. Humboldt, p. 57.

† Phil. Trans. 1750, vol. 46.

nation more or less; hence many of the needles and cards he examined appeared to have a very small directive force. The needles employed in the navy were made of a single piece of spring-tempered steel (87), broad toward the ends, which were pointed, and tapering toward the middle, as represented in the annexed Fig. 132. This form, although less objectionable as to direction, was still imperfect.

Fig. 132.



Such needles, he says, acquire six poles (26); these may be made apparent by the experiment with steel filings (28). The needle has not, from this circumstance, the same amount of directive force; the greatest directive force obtains when the magnetic curves extend from two polar extremities. Dr. Knight concludes, after a careful inquiry, that a regular parallelopiped, or straight bar narrow-edge needle, as represented in the annexed Fig. 133, is the most advantageous form for a compass-needle. He thinks that if the hole at *c* for the suspension-cap could be avoided, it would be very desirable, and for the reasons just assigned. With this view he was led to suspend the bar upon an agate attached to its under surface, the card being secured beneath the bar through the intervention of a ring of brass, of sufficient weight to bring the centre of gravity of the whole system below the point of suspension. Such was the form of needle and card afterward in use for some time in the royal navy; and it is still worthy of serious attention, how far this kind of suspension may not be improved in its application to the light talc discs now employed, so as to avoid the weight of the brass ring. As, for example, in the way indicated in the annexed Fig. 134, in which *a c b d* represents a light disc of talc, attached by two fine wires at

Fig. 133.

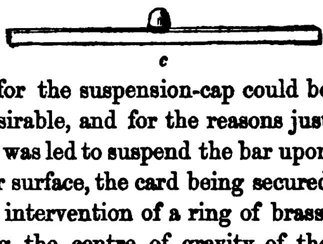
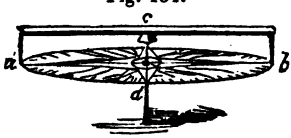


Fig. 134.

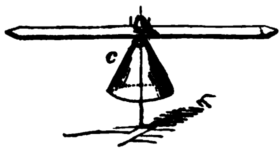


the extremities of the bar; *c*, the point of suspension which is beneath the bar; *d* the standard of support.

It is not unworthy of remark, that the Chinese method of suspending the compass-needle, already described (122), is based on the same principle; the point of suspension in the Chinese compass is invariably below the centre of gravity of the needle, the needle being perfectly continuous. The sensibility and delicacy of these instruments are quite surprising.

The Dutch employed for several years a conical brass bell in the suspension of their compasses, which they attached below the centre of the needle, as indicated in the annexed Fig. 135. All these contrivances, however, became eventually superseded by a simple suspension-cap, fixed in the centre of the needle, as at *c*, Fig. 133; but of all the methods of suspending the magnetic needle, that by means of a silk fibre (118), is undoubtedly the most delicate although not perhaps sufficiently practical for sea-going purposes.

Fig. 135.



285. Dr. Knight further inquires as to the best material for the cap of suspension. The caps at that time in use were either made of brass, or a hard, mixed metal, similar to the metal of a reflecting telescope, or otherwise containing a centre of crystal or agate. The first, he says, will only admit of a brass point; the others being costly, he was led to try glass; but upon the whole he concludes that a cap centred with agate has the least amount of friction. For a point he chose a common sewing-needle. Of late years the centres of the caps of compass-needles have been occasionally formed of ruby, and a point employed for their suspension formed of native alloy, which is found to be harder than steel.* This question is one of much consequence to the working of

* A valuable practical paper, by Capt. Johnson, R.N., on this subject, will be found in the Reports of the British Association for 1840.

a ship's compass; the great weight of the needles and cards at present employed, is very liable to work a hole in the agate centres, especially when at all defective in structure; and so eventually destroy its action; hence it is still very doubtful whether a fine and well-hardened point of brass, worked to fit a central cap of hard mixed metal, is not after all as well adapted for the purpose of a delicate and lasting suspension as any which can be devised. Mr. Stebbings, a celebrated optician at Southampton, employs ruby for the points as well as the caps, worked to fine globular surfaces of contact.

286. The question of the most favourable conditions in the construction of a compass-needle was, in the year 1821, further investigated by Capt. Kater, F.R.S., who came to the conclusion that the best form was the pierced rhombus (Fig. 131); that hardening the needle throughout was injurious to its capacity for magnetism, and that the directive force depended on the mass, and not on the surface. These deductions have not certainly been so satisfactorily confirmed as to entitle them to unlimited confidence; indeed, it is now universally admitted, that a bar of small breadth, Fig. 132, suspended edgewise, and hardened throughout, as practised by Gowan Knight, is after all the best form for the needle of the mariner's compass: this kind of needle, therefore, is usually employed.

Captain Kater's conclusion, that the directive force of a magnet is dependent on its mass, has yet to be reconciled with the fine experiments of Professor Barlow (239), and the more recent inquiries already adverted to (228).

287. It may be worth while to notice a few conclusions arrived at by Michell and some of the old writers on this subject. Michell observes that all single unarmed bars should have a certain length, in proportion to their weight. A bar 6 inches in length, and $\frac{1}{2}$ an inch wide, should weigh $1\frac{3}{4}$ ounces. The steel must be free from veins of iron, and

* Phil. Trans. for 1851.

hardened with a full heat, but not with too great a heat; for that is as bad as the other extreme. That is the best steel which will receive the greatest hardness with the least degree of heat.

Michell recommends very light bars for the purpose of a compass-needle, because the friction, he says, increases in a much greater degree than the magnetic power; he recommends the caps for such needles to be of gold alloy, the alloy in large proportion. He found a long needle with this cap to vibrate on an irregular blunt brass point for fifteen minutes, whereas, with a common brass cap, and a sharp steel point, it would scarcely vibrate at all.

Mr. Timothy Barlow, in a good practical work,* in which he treats of the "fashion of the compass-needle," says that the steel must be first hardened to brittle hardness; it should be anointed with soap before being put into the fire, by which the black will easily scale off. The needle is to be now placed on a bar of red-hot iron; when "you shall see it turn from white to a yellowish colour, and then to blue;" now throw it on a table and let it cool; and "so he is of a most excellent temper." For the form of the needle he approves of an open ellipse, but is a great advocate for light cards and needles.

288. Having already considered the questions relating to the kind of steel, temper, and methods of magnetizing (89) (99), it will not be requisite to enter further upon these questions here. We have merely to observe, that in the construction of bar-needles for the mariner's compass, it has been thought of advantage to employ two or more magnetized steel plates, and unite them into a sort of compound magnet (19, 113). The Rev. Dr. Scoresby, at the Bristol meeting of the British Association, in 1836, first proposed this method for compass-needles, and insisted on the necessity of tempering the plates throughout their length. Compound bars of thin steel plates, on Scoresby's construction,

* Magnetical Advertisements; London, 1616.

have since been employed for the compasses of the royal navy.

289. It was customary, above half a century since, to apply more than one needle to the same compass-card; this practice has of late years been again revived, with additions and improvements, more especially in the compasses of H.M.'s ships; in which from three to five needles have been employed. Cavallo, whose works on electricity, magnetism, and other branches of physics, are highly prized in the world of science, has in reference to this practice the following remarks:—"Compasses for the sea service formerly, and some even at present, are made in the following improper manner:—The brass cap is fastened to the middle of a circular card, upon which the various points of the horizon, as the east, west, &c., are marked. On the under part, two pieces of magnetic steel are stuck fast to it, so as to be parallel, and to stand about half an inch distant from one another, the pin upon which the whole is suspended passing between them."* The object in using more than one needle is evidently a greater directive force; this advantage, however, as observed by Professor Barlow, cannot be obtained without an increase of weight of steel, and as a necessary consequence, a greater amount of friction on the point of suspension. Unless, therefore, the directive force increase in a greater ratio than the loss by friction and wear of the centre, little advantage is obtained. The only favourable circumstance is in the case of heavy cards, made purposely heavy, in order to steady the motion likely to be induced in it by the rolling and pitching of the ship. If the card be encumbered by a dead weight, the power of a single needle is frequently insufficient to bring it accurately into its meridian, and thus the essential quality of the compass is sacrificed; now, by employing several bars, we not only add to the weight of the card, but we also add directive force,

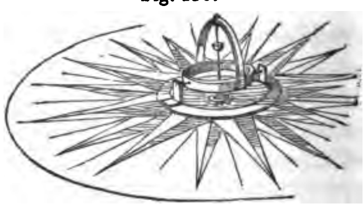
* Treatise on Magnetism, by Tiberius Cavallo, F.R.S.; London, 1800.

and thus in great measure avoid this defect. It will be found, however, as we shall presently show, that the use of more than one bar-needle and heavy cards are quite unnecessary; any method of steadying a compass by mechanical impediment to motion, whether by friction on the point of suspension, or on any other point, is evidently a hazardous practice. The mariner, deceived by the apparent steadiness of the compass-card, may find himself in peril before he is aware of his danger, the impediment to motion being such as to place the compass in error as to direction.

290. As a great and almost endless variety of forms and contrivances for the mariner's compass, with a view to its further improvement, have been proposed, it may not perhaps be undesirable to advert to some of these inventions.

Compass by Preston and Alexander.—The great contrivance universally resorted to for the purpose of meeting the difficulties arising from the pitching and rolling motions of the ship, is, as we have already explained (148), the method of gimbalds, by which, under any inclination, the compass-bowl remains vertical. In Preston's compass, an inner and small set of gimbalds are applied also to the needle and card, the whole resting by a descending point upon an agate centre, as shown in Fig. 136. This agate centre is further preserved vertical and steady by means of a pendulum action, and a ball and socket joint, not drawn in the figure. The interior gimbalds, &c. have been found very beneficial in preserving the needle and card steady.

Fig. 136.



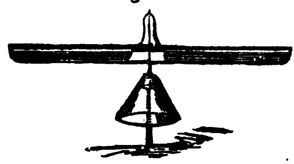
Mr. Grant Preston also contrived another kind of compass, in which the needle and card were fixed on a vertical axis moveable between two centres, and in 1832 obtained a

patent for steadying the needle by passing a delicate-pointed axis of support through a fine hole in a semicircular arc, or plate of brass, attached beneath the needle.

Pope's Compass.—In this compass, two or more bar magnets are now employed. They are set parallel, and allowed to take any degree of inclination of which they are susceptible; each bar being hung on a transverse horizontal axis, applied to pivots fixed to slits in the compass-card. The freedom of motion of the needles in a vertical plane may certainly be useful in high latitudes; but beyond this, no advantage is derived from it. This compass originally had only one needle hung in the centre of the card.

Compass by Captain Walker, R.N.—In this compass, a double set of suspensions are employed, one over the other. First, the card is suspended on a fixed vertical axis, passing through a small hole in a plate of brass, attached to the under side of the needle, upon Mr. Grant Preston's principle, and terminating in the agate cap, which is somewhat elevated. This axis of support is fixed upon a conical bell of brass, such as formerly employed in the Dutch compasses, and shown Fig. 135. This bell is again suspended on a point and agate centre beneath, as represented Fig. 137. The object contemplated, is a steadying of the needle by a refinement on Preston's patent, and a decrease of friction, by allowing motion to the point of suspension of the needle through the intervention of the brass bell. The bell, however, may be fixed, if found desirable, by means of a wooden cone, which is to be placed within it, over the point of suspension.

Fig. 137.



The needle may be considered as a sort of combination of the flat and bar-edged needles, the latter being nearly divided in the centre, but extending edgewise under the flat bar up to its extremities, as indicated in the figure.

Compass-Needle by Captain West, R.N.—The oscillations and movement of the needle are checked by the occasional friction of an ivory ring, through which the vertical axis of suspension freely passes. The ring is fixed centrally beneath the needle by means of a semicircular arc of light brass wire, attached to each of its extremities, as in Preston's patent. This contrivance has been found effectual.

Compass by Captain Boutakoff, of the Imperial Russian Navy.—The needle is fixed nearly in the line of the dip, which can be changed to suit the latitude; the card is figured on each surface, and so fitted that, in crossing the magnetic equator, it can be turned over with the needle. Captain Boutakoff thinks that by this method he avoids at least one-half the vibration.

Dent's Compass.—In this compass four thin, wide magnets of steel plate are applied edgewise to the under surface of the card, parallel to each other, and the whole is fixed on a vertical steel axis, as practised by Preston, but is beautifully set up between two jewels as centres, after the manner of the balance of a chronometer; so that very little friction arises in the pivots of the axis. The centre of gravity and centre of motion are made to coincide. To check any inconvenient oscillation, there is a light steel spring: this spring, by a simple lever action, may be pressed gently against the axis of the compass.

Stebbing's Compass.—The needle and card are suspended on a ruby point and agate centre, which are carefully worked to extremely fine spherical and corresponding surfaces of contact; so as to avoid all abrasive action, the compass-fly is of silk, secured in a light circular frame of brass attached to the needle; the whole is enclosed in a glass bowl, and is perfectly transparent. This compass is usually fitted in the deck, so as to be illuminated at night by the lights in the cabin beneath.

Submerged Compass.—About the year 1779, Dr. Ingenhouz made some experiments on a magnetic needle immersed

in water. He found that the water by its resistance as a medium, tended to steady the needle, without diminishing in any sensible degree the directive force. This led him to think of enclosing the needle for sea purposes in some fluid; a proposition which, although deserving much consideration, was not at the time adopted. It has, however, since been partially resorted to, and some instruments of this kind by Crowe and Preston have answered extremely well. The compass-bowl or kettle (148) being fitted water-tight, is filled with oil or spirit, or some fluid compatible with the durability of the compass. This instrument is occasionally employed in the royal navy, and is found especially useful in boats when subjected to a short jerking motion.

291. *Admiralty Compass.*—The admitted defects in the compasses formerly supplied by contract, by the lowest tender, for the use of the royal navy, induced the Board of Admiralty, in the year 1820, to appoint Professor Barlow to examine the compasses then in store. Mr. Barlow found these instruments so defective, that, as already observed, he states, in his report, "at least one-half were mere lumber." Very little amelioration, however, in this state of things appears to have taken place until 1838 to 1840, when the board appointed a committee for further inquiry. One of the results of the investigations by this committee has been the production of a compass called *par excellence* "the Admiralty Compass." In this compass four of Scoresby's compound magnetic bars are employed, secured together with the card within a light ring of brass; the card is of mica, covered with thin paper, the impression of the cardinal points, &c., being struck off subsequently to its being cemented to the surface of the talc, so as to avoid all distortion of the surface by shrinking; the caps are of agate or ruby, worked to the shape of the points of suspension, which are of native alloy (285). Spare points of steel are also supplied; these are gilded by the electrotype process. The compass-bowl is made of copper, with a view to tranquillize the oscillations of the needle,

after a form of compass previously submitted to the committee by the author of this work. The principle, however, as thus employed, is very inefficient, the great condition being the application of a dense ring of copper immediately round the poles of the needle. Each compass is furnished with two spare cards, a light and a heavy card, and six spare pivots. When the light card is not sufficiently steady, then the heavy card is directed to be employed, together with the particular pivot-point especially appropriated to its use; the card is levelled by balance slide-pieces, as in the compass previously submitted by the author for the consideration of the committee.

This compass, although not possessing any superior excellence as a steering compass, having, with a sensible suspension, proved very unsteady at sea,* is nevertheless carefully and beautifully constructed, especially in its adaptation to the purposes of an azimuth compass, into which form of compass (150) it is convertible. In this case the instrument is placed on a stand, the glass cover removed, and the azimuth circle fixed on its upper margin. The arrangement is such that the sight-vane and prism (150) can be turned without interfering with the other parts of the instrument, as will be hereafter explained (298). The bottom of the compass-case also can be removed so as to light the card from beneath.

292. Upon a review of nearly all the several forms of mariner's compass to which we have just adverted, it is evident that the simplicity of construction requisite to every sea-going instrument has been materially compromised, all the contrivances are more or less complicated, and, as a necessary consequence, more or less costly. That would

* See a valuable work by Capt. Johnson, F.R.S., Capt. R.N., "On the Deviations of the Compass," p. 51, published under the sanction of the Lords Commissioners of the Admiralty, as also reports from H.M.'s ship *Asia*, and some other vessels.

be the great perfection of the mariner's compass which should combine steadiness, under the variable motions of the ship, with great sensibility and simplicity of construction, so that in case of any mishap or error arising from the wear and tear of the respective parts, there may be nothing to correct, which any ordinary mechanic, or, if in the navy, which the ship's armourer could not easily manage. Unless, therefore, it can be shown that such complex arrangements are absolutely requisite, they are best avoided. No sufficient reason, for example, can be assigned for the employment of from three to five compound magnetic bars of costly and difficult construction; supposing it were proved, from the evidence of experience, as well as theoretically, that a single and simple bar-edged needle is even more than adequate to any required practical purpose. Beside this, there are some not unreasonable objections to the use of several bar-needles; the similar poles, for example, tend to destroy each other's power (111); and if the magnets be not very accurately parallel, and carefully magnetized and placed, the card may be in error as to direction; to avoid this, it is requisite to suit the card to the direction after the needles are applied.

We may further observe, that it would be unphilosophical to employ two cards of unequal weight, with especial pivots adapted to each card; and with a view to particular adjustments under motion, and to the obtaining a steady compass by the aid of friction, provided all the advantages to be derived from such adjustments could be arrived at with one card, and by more simple and efficient means; it would also be quite superfluous to mount a compass on two consecutive pivots, as in Fig. 137, when one point of suspension is sufficient. Such arrangements, therefore, however ingenious, are not desirable, unless absolutely requisite to the perfection of the instrument. It is to be remembered that, in the construction of the mariner's compass, the abstract

perfection we seek to obtain, is the image of a small horizontal circle duly graduated, and divided into thirty-two rhumbs or points, which, floating as it were in a fixed position in space before the eye of the steersman, directs the guidance of his ship. It is, in fact, the ship which we must suppose to move into various positions, not the compass; that should be so delicately and sensibly hung as to come as near the condition of this ideal aërial compass as may be.

293. *Mariner's Compass by the Author.*—Impressed with these views, the author of this work was, in the year 1831, led to the construction of a particular form of mariner's compass, combining simplicity of construction with great sensibility and stability. The following is a brief notice of this instrument, as constructed by Messrs. Lilley, opticians, Limehouse:—

The needle consists of a light bar-edged magnet, from 5 to 7 inches in length, furnished with a central cap, as in Fig. 133. The bar is carefully worked, hardened and tempered throughout; and, previously to being magnetized, is accurately poised in a horizontal position (156).* Being thus poised, two small sliders of silver, weighing each about twenty grains, are fitted to the bar, so as to move upon it with friction. They are placed over a mark midway between its centre and extremities, the whole being perfectly poised; the bar is now rendered magnetic, and in such a manner as to admit of the centre of the various magnetic curves (28), Fig. 16, falling immediately on the point of suspension. The small magnetic dip incidental to the bar, is corrected by moving one of the silver sliders a little toward the centre, and the opposite slider a little toward the extremity. By this method, we have always what may be considered as the same quantity of magnetism, matter, and motion, on each side the centre, since the difference in the angular inertia of the silver

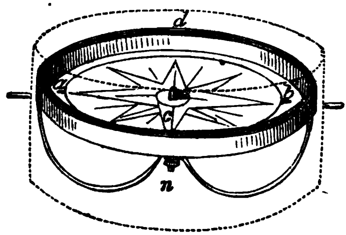
* This instrument has become the property of Messrs. Lilley & Son, opticians, West-India Docks, and is made with great care and perfection in the workmanship.

sliders is sufficiently small to be neglected; the bar, therefore, is so far deprived of any tendency to persevere in a state of movement, from the motion of the ship. The magnetic force of this bar-needle, from the particular way in which it is made, is so considerable, as to lift at either pole three times its own weight of iron, and will produce, according to Scoresby's method of deflections (134), a deviation of 22° at a distance of twice its length from the centre of the trial-needle. These bar-needles are nevertheless very light.

The needle as thus constructed is attached to a very light disc of talc, in a single piece, and on which the requisite points and graduations are conspicuously and clearly painted; by which means the presence of a paper surface is avoided. The whole is balanced in an east and west direction, that is, transversely to the direction of the needle, by a light cross bar of brass, furnished with small sliders, in the way just described.

Things being thus arranged, the needle is suspended upon a central point *c*, Fig. 138, proceeding from a double curved bar *a n b*, fixed as a diameter to a dense ring of copper *a c b d*, and in such way as to admit of the poles of the magnetic needle *a b* moving just within the ring, and so near the copper, that the magneto-electrical action already explained (58, 60, 63), can sensibly restrain any oscillation to which the needle may become exposed. We thus bring to bear upon the needle an invisible agency, which, without offering any rude, common, mechanical impediment to motion, such as friction, or in the least degree interfering with the sensibility or direction of the instrument, restrains as if by a magic hand its disturbed movement, and confines it like the

Fig. 138.



ideal card to which we have adverted, in a given position in space.

294. The author has investigated* the magnetic conditions of this phenomenon, and has shown that the restraining force with a magnet of a given power, is as the quantity of the copper within the sphere of action directly, and as the squares of the distances from the magnetic polar extremity of the needle inversely (174, 175), the matter of the copper being supposed to be condensed into an indefinitely thin stratum, and taken at a mean distance from the pole of the bar at which the sum of the forces may be supposed to produce the same effect as if exerted from every part of the mass. The energy of a ring of copper in restraining the magnetic oscillation is therefore as its density. It was also further found that with a given magnetic tension the restraining power of the copper no longer sensibly increased with the thickness of the ring, and that hence the required thickness was different for different needles. It is requisite, therefore, to have the poles of the bar as near as possible to the surface of the ring; to give the copper the greatest possible density, accumulate it immediately about the poles of the needle, and give the ring a greater or less degree of thickness sufficient to exhaust as it were the magneto-electrical energy of the magnet to be employed.

The ring and axis of suspension are accurately turned and centred in a lathe; the axis of support *c*, Fig. 138, is pointed at each extremity, and admits of being reversed in position by turning it over, and fixing it in the reverted direction; we have hence a spare point always at command. The cap, also, can be renewed when requisite. The points and centres are usually made of very hard mixed metal, which has been found less liable to abrasion than agate and steel points.

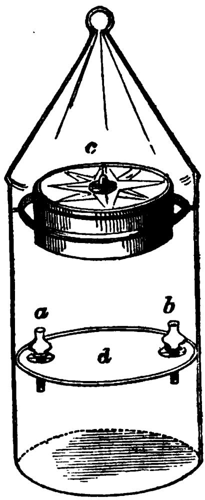
Things being thus prepared, the whole is placed within a cylindrical copper case, faced above and below with plate-

* Phil. Trans. for 1831, p. 497.

glass covers. As indicated in the last figure, the whole is hung in gimbalds, in the usual way (148).

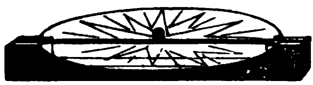
295. The card being beautifully transparent, a small quantity of light placed beneath, and a little on one side of the compass, is sufficient to illuminate it at night. With this view, it is intended either to fit the compass in the deck, and light it from the cabins beneath, or otherwise, in a binnacle of a very simple construction, shown in the annexed Fig. 139, especially adapted to its use. This binnacle is of wood, and of an octagonal or cylindrical form, about two feet six inches high, the compass being hung on its upper part, at *c*. About twenty inches beneath the compass, there is a platform *d*, carrying two small spring candle-lamps *a b*, hung on pivots in holes in the platform, one on each side; one of these is sufficient for the purpose of illumination. The candles are easily replaced without disturbing the apparatus, they being previously secured in spare spring sockets, made to drop freely into the body of the lamp, which need not be taken out. There are some small holes round the compass at *c*, for ventilation, and a small door below, through which the requisite manipulations are easily carried on. This method of illumination is extremely economical, clean, and efficient, and requires no trimming or attention. It is far superior to the common method with oil-lamps,* which occasionally proves very troublesome, dirty, and inconvenient.

Fig. 139.



* The compass may be illuminated in this way at the rate of one penny for seven hours, the effect being a subdued and beautifully soft transparent

Fig. 140.



a b

296. When the card and needle are not in actual use, they are to be secured in a soft iron keeper (10), as indicated in the annexed Fig. 140, which represents the needle as resting in slits, cut for its reception in two masses of soft iron, formed at the extremities of a soft iron bar *a b*; this keeper is fixed in a shallow square box, with a slide cover. It is most important to the mariner to attend to the preservation of his compass in some such way as this. The instrument as usually stowed in the store-rooms on shipboard is very liable to be ruined in various ways, and its polarity either greatly weakened, or altogether destroyed (110). If the north pole of the needle be merely placed in opposition to its natural direction, and toward the south pole of the earth, that alone is sufficient to disturb and weaken its magnetic development (14, 101).

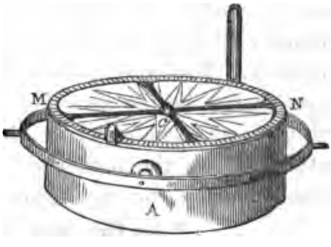
297. It not being the author's object to dwell longer on this particular form of sea-compass than is requisite to the interests of navigation and scientific inquiry, any lengthened report of its operation, as observed in numerous instances, must necessarily be avoided: we may, however, observe, that it has been extensively and very successfully employed in the merchant navy; it has been also employed in the fleets of the Honourable the East-India Company, in numerous ships of foreign powers, and in several of Her Majesty's ships; and it appears, upon the whole evidence of experience in every class and kind of vessel, that there is no condition requisite to the full practical perfection of the mariner's compass which it does not satisfy; and considering the extreme perfection and beauty of the workmanship by

light. The lamps and candles are supplied by Mr. S. Clarke, 55, Albany Street, Regent's Park, London. The candles are warranted to stand in any climate. Three years' consumption may be packed in a box occupying about two square feet.

the makers, its cost is comparatively small, it being about half that of the Admiralty compass as commonly supplied to the ships of the navy. In the heavy seas about Cape Horn and the Cape of Good Hope, the card was not found to oscillate more than from $\frac{1}{4}$ to $\frac{1}{2}$ a point each way. The only complaints which have arisen, in a few instances, have been referable to abrasion of the agate centre in some of the instruments first made, arising from wear and tear of the point of suspension. The agates, in these cases, were examined, and found defective; all such defects have been since removed. It may not be unworthy of remark that this compass has proved especially steady in steam-ships fitted with the screw propeller.

298. The application of magneto-electric action as a means of steadying the compass in its meridian is of singular importance to the azimuth compass (150), where angular distances require to be accurately measured. An improved azimuth compass, by Messrs. Lilley, has been lately produced, in which the needle, nailed as it were to its meridian by the influence of a dense ring of copper, may be considered as being without any oscillation. In this instrument the margin of the card is graduated to twenty minutes, the plate-glass cover contains a metal centre, about this centre the pivot of the upper part of the verge, carrying the sight-vane and prism (150), revolves, leaving the compass-bowl and its contents fixed, as in the azimuth compass of the Admiralty committee; all this part of the instrument, therefore, remains unaffected: this is of the utmost importance, especially in iron ships. The lubber-line in this instrument, as constructed by Messrs. Lilley, is set on a delicate index, which acts

Fig. 141.



as a stop when the reading is being taken, and is always directed to the ship's head. In the annexed Fig. 141, M N represents the revolving part of the verge, which can be turned about the centre *c* fixed in the glass plate beneath; A, the body of the instrument, remaining fixed.

299. It may not be unimportant, before dismissing the consideration of magneto-electricity as a restraining force in the disturbed movement of the compass on ship-board, briefly to notice a conclusion arrived at by the compass committee of the Admiralty relative to the operation of this force, the question being one of singular importance to the future interests of navigation. The author had, six years previously to the appointment of the committee in 1837, completely worked out all the great practical deductions bearing on the application of magneto-electrical action in steadying the movements of the mariner's compass, and had shown how the magnetism of the needle itself might be made the means of restraining its own oscillations. The questions of thickness of metal, density, and magnetic force had all been completely investigated by taking the magnetic vibrations within thin concentric circular laminæ of copper turned up in the form of rings.* It was easy to determine with a given magnet, and by means of the formula previously deduced (66), the precise effect of any one of the concentric rings, both as to position and distance, or of any number of rings combined, or by varying the magnetic force, the effect due to different degrees of magnetic power; in this way, as already observed (294), it was proved that the magneto-electric energy, or restraining force, was as the magnetic intensity directly, and as the second powers of the distances inversely. The experimentalists of the compass committee, however, not having probably considered these facts, were led, upon an examination of the compass submitted by the author, to try the influence of a solid copper bowl, of a given thickness, on the magnetic oscillations, and then to

* See Phil. Trans. for 1831, p. 497.

cut away or turn down the bowl $\frac{1}{10}$ of an inch at a time, so as repeatedly to reduce its substance; examining as repeatedly the magnetic oscillation at each reduction. The conclusion arrived at by the committee was, that a thin bowl of copper was as efficacious in restraining the magnetic vibration as a thick bowl; and that hence if the magnetic needle and card were enclosed in a copper compass-kettle, the use of a copper ring condensed about the poles of the needle, as employed by the author, would be superseded. Upon this very hasty conclusion the committee proceeded to act in the construction of the Admiralty compass. With respect to the experiment itself, it was anything but refined: perhaps it may be considered as somewhat clumsy when compared with the method of concentric laminæ. For the force decreasing as the second powers of the distances inversely, it was, after all, not likely that any great effect would result from the distant parts of the bowl; the induced restraining force would be almost entirely, if not altogether, confined to that part of the copper bowl immediately opposed to the poles of the needle: the experiment, therefore, was most unnecessarily elaborate and costly. It is certainly possible that a magnet of a limited power, with its poles placed at a certain distance from the copper, might have all its magneto-electrical induction exhausted as it were, by a certain thickness of copper, as the author had already shown. This, however, was only a limited or particular case of a great physical action, but which the committee failed to investigate in all its generality. Had the experimentalists tried other magnets, and allowed their poles to oscillate near the surface of the copper, they would not have come to the same conclusion.

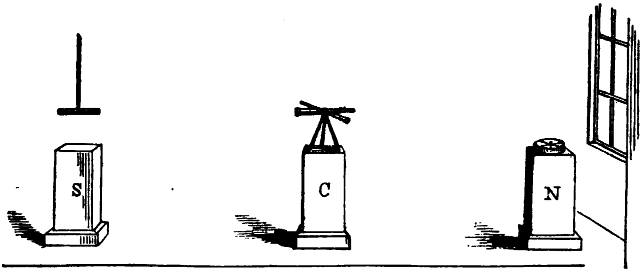
The experimentalists, however, had great confidence in their deduction; but they evidently failed in producing any amount of tranquillizing power; since, by the extract from the work published under the sanction of the Board of Admiralty, already referred to (285), as also from various

official reports, the compass proved "too unsteady for use under the heavy rolling motions of a ship of the line," also in "some steam-vessels;" it hence became requisite to call in the aid of friction by the employment of a heavy card, in order to curb the irregular movements.* The experiment, therefore, by the compass committee was incomplete, and the deduction from it practically false: to obtain anything like a competent tranquillizing power, it is absolutely requisite to employ a powerful bar, and place the copper in a thick dense ring, immediately about the poles of the needle. It is in fact notorious to all those acquainted with the Admiralty compass, that little or no effect is produced by the influence of the thin copper bowl on the oscillations of the card. This subject is undoubtedly important, and is still open to much further and beneficial investigation. The most energetic metal has yet probably to be discovered.

300. *The Compass and Magnetic Observatory.*—Much benefit did undoubtedly arise to the public service by the appointment and labours of the committee of inquiry into the state of the compass department of the navy, more especially in the establishment of a regular and well-ordered observatory at Woolwich, for examining and perfecting the compasses intended to be employed in H.M.'s ships; and it is to be regretted that a full report of the committee's proceedings has never appeared. The observatory is placed in a suitable and well-selected position in the parish of Charlton, near Woolwich; it has a convenient room built of wood, apart from the rest of the establishment, especially prepared for experiments in magnetism, and the examination of sea-compasses, to which it is devoted. The method of testing a compass is as follows:—Three pedestals, S, C, N, Fig. 142, are firmly fixed in the room, quite independent of the floor, in the line of the magnetic meridian. The south pedestal S carries a suspended magnet, which is observed by means of a transit telescope fixed on the centre pedestal C; on the pedestal N

* Johnson on the Deviation of the Compass, p. 41.

Fig. 142.



is placed the compass to be examined. The collimating magnet S consists of a hollow steel cylinder, ½ an inch in diameter, and about 6 inches in length, centrally suspended in an appropriate frame by a long silk fibre; a small lens is fixed in the north end of the cylinder, and there is an extremely fine scale of 160 divisions traversing it horizontally, and right across its centre. The transit on the central pillar C being duly adjusted and directed in the axis of the collimating magnet, its scale is observed to vibrate across fine filaments of spider's web, fixed perpendicularly in the tube of the telescope. The magnetic meridian being found by this means, the transit is turned over, and directed toward the north, upon a mark painted on a distant wall on a rising ground, called Cox Mount; this mark corresponds to the line of the collimating magnet on pedestal S; we thus transfer over, as it were, the line of the magnetic meridian as taken in the telescope upon the compass to be examined, and which is placed on the pedestal N. The needle and card being removed, the compass is so adjusted in position by appropriate apparatus on which it rests, as to bring the point of suspension of the needle in the line of the telescope, and so as to bisect it; this done the card is replaced, and its north pole is made also to coincide with the line of the telescope.

For the adjustment of the azimuth compasses there are a

set of graduated divisions painted on the distant wall, and the vertical line of the telescope conveyed through the window so as to cut these divisions; the prism is now adjusted for the zero point of the card, the hair-line of the sight-vane (150) being directed to the particular division on the wall, cut by the vertical line of the telescope.*

The pivots, caps, and gimbalds, and the metal of the compass-bowl, &c., are now carefully examined; also the magnetic power of the needles, which are tested by a standard magnetometer of deviation (134), so that errors liable to arise in any particular instrument are certain to be detected.

301. Attached to the Observatory is a museum containing a collection of sea-compasses of various kinds, and also other magnetic instruments. The following is a brief notice of some of the forms of mariner's compass found in the establishment:—

Compass by Mr. George, Master R.N.—The needle is a plane circular segment of thin steel plate, vertically placed above the card. The point of suspension is on a gimbald inside the kettle.

French Binnacle Compass.—A descending point rests on an agate plane, the position of which can be changed so as to renew the surface of suspension.

Compass by Preston.—Card and needle on a vertical axis, moveable between two centres; a method since adopted by Dent.

Compass by James Thomas—Has an axis of suspension, through a plate, as first employed by Preston, and since adopted by Captain Walker (286), Fig. 137.

Compass by Crowe, of Feversham.—The card is hollow, and of enamellèd copper, placed in a fluid; it is buoyed up centrally against a point projecting downward from the glass cover. This was the original fluid compass (286).

Compass by Captain Kater—Has a double suspension, an upper suspension of silk fibre, so as to take the weight off the point beneath.

Old Prismatic Azimuth Land Compass.

Danish Azimuth, as employed in the Danish royal navy, has a telescope of observation, fixed across the azimuth circle. The gimbalds work on friction rollers.

* Two of the plates of glass in the window are worked perfectly plain, so that no error may arise in this operation.

Azimuth Compass by Sydes and Davies.

Azimuth Compass by Blunt, of London.—A very old form.

Meridional Compass by Walker—Has a graduated concave arc over the card.

Compass by Wood, of Liverpool.—A cylindrical pointed magnet, of about 10 inches in length; is fitted to a system of graduated metallic circles, the whole set on a vertical axis.

Compass by Miller, of the Devonport Dockyard.—The needle is bent each way from the centre to about the angle of the dip, and is compounded of the flat and bar-edged needle.

Boats' Compasses of various Kinds.

Chinese Compass.—The needle is suspended on a point below its centre of gravity.

Binnacle Boat Compass by Preston.—A fluid compass. The fluid is one-third alcohol and two-thirds water.

Compass by Captain Phillips, R.N.—The needle is elliptical; the compass is on springs, and without gimbalds. It is poised on a central point, so as always to remain vertical.

Compass by Sir Edward Owen—Is hung on springs from the box, so as to yield to the concussion of guns.

Compass—Set in double gimbalds.

Spanish Compass.—The bowl is of wood; the card pasteboard.

Insulated Compass—Is set on glass legs.

Compass by Lieutenant Edye, R.N.—The needle is hung centrally by attraction at the pole of a vertical magnet, as occasionally practised in the chemical balance.

Experimental cards with various needles and pivots; about forty employed by the Committee.

Card in which the line of suspension may be adjusted to the axis of the gimbalds.

Patent Compass by Jennings.—The needle is within a hollow metal case, containing ferruginous matter.

Pope's Original Compass.—The needle is a flat bar, hung on a central axis, free of the card, so that it may take any dip.

The magnetic needle of the dipping instrument employed by Captain Cook.

Proposed Card by Captain Milne, R.N.—For meeting the deviations of local attraction. The card is figured for direction indicated in the ship.

Patent Card by Captain Sparkes, R.N., adjusted upon similar principles.

This observatory, so essential to the interests of the

navy, is under the direction of an intelligent naval officer, Captain Johnson, who is well versed in the science of magnetism, and is at the head of the compass department of the Admiralty.

302. The card of the mariner's compass, as we have before explained (144), is commonly estimated in terms of 32 points or rhumbs ;* it has, however, been found desirable for more refined purposes to estimate the angular deviation from the line of the magnetic meridian in degrees and minutes, taken in reference either to the north or south pole of the card; thus, instead of the rhumb N.E., we say N. 45° E.; instead of S.S.W., we say S. 22° 30′ W., and so on. The following, as a table of reference, may not be altogether superfluous.

Points.	Deg.	Points.	Deg.	Points.	Deg.	Points.	Deg.
	° ′		° ′		° ′		° ′
N.	0 0	E.	90	S.	0 0	W.	90
N. by E.	11 15	E. by S.	78 45	S. by W.	11 15	W. by N.	78 45
N.N.E.	22 30	E. S. E.	67 30	S.S.W.	22 30	W.N.W.	67 30
N.E. by N.	33 45	S.E. by E.	56 15	S.W. by S.	33 45	N.W. by W.	56 15
N.E.	45	S.E.	45	S.W.	45	N.W.	45
N.E. by E.	56 15	S.E. by S.	33 45	S.W. by W.	56 15	N.W. by N.	33 45
E.N.E.	67 30	S.S.E.	22 30	W.S.W.	67 30	N.N.W.	22 30
E. by N.	78 45	S. by E.	11 15	W. by S.	78 45	N. by W.	11 15
E.	90	South	0 0	W.	90	North	0 0

It is easy to observe here, from the north or south line, or 0° 0′, either in the upper or under line of the table, the degrees corresponding to any rhumb taken either east or west of the meridian. Thus we have for the rhumb E. by S. the expression S. 78° 45′ E.; for the rhumb W.N.W. we have the expression N. 67° 30′ W.

It has been further found convenient, in some especial instances, to take the angular measure from the north point only, all round the circle and in an east direction. Thus we should have for S.S.W. the expression N. 202° 30′, for N. by W. we have N. 348° 45′; it is further evident that

* The reader is requested to correct the following errors of the press in the table given p. 133, Parts I. and II. line 4, under E. read S.E. by E.; line 3, under S. read S.S.W.; line 4, under S. read S.W. by S.

we may represent in this way the position of any rhumb from either of the cardinal points N., E., S., W. taken as 0° 0′ in each quadrant. Thus we may represent E.N.E. as E. 22° 30′ northerly, taking E. as 0° 0′. The method, however represented in the table just given is that commonly employed.

303. *Local Attraction.*—By the term local attraction, as applied to a ship, we are to understand a certain disturbance of the compass under the influence of the general mass of the vessel considered magnetically, in virtue of the iron which it contains. The amount of disturbance will materially depend on the direction of the ship's head in respect to the needle, by which the ship's position as a magnet is varied (191). It is now but too certain that errors of the compass thus produced have led to afflicting cases of shipwreck. We owe the first intelligible notice of the local attraction of a ship to Mr. Wales, F.R.S., who accompanied Captain Cook as the astronomer of his expeditions in 1772-3-4. Mr. Wales observed, in the English Channel, differences in the azimuth compass of 19° to 25°, and afterward similar discrepancies all the way from England to the Cape. The greatest westerly deviations occurred when the ship's head was between N. and E. He was hence led to express his conviction, "that variations of the compass (149), observed with the ship's head in different positions, and even in different parts of the ship, will differ materially."* This was certainly the first notice of local attraction scientifically observed, and must not be confounded with notices of the common action of iron on the compass, mentioned by earlier navigators.†

304. In the year 1790, Mr. Downie, master of H.M.'s ship *Glory*, made an interesting report on this subject, in which he observes, "that in all latitudes, at any distance from the magnetic equator, the upper ends of iron bolts

* Wales's and Bayly's Observations on Cook's Voyages, p. 49.

† Sturm's Mariner's Magazine, published 1684. Dampier, 1680.

acquire an opposite polarity to that of the latitude,"—an observation in accordance with Marcel's experiment in 1772 (101); so that by induction they may attract or repel the north end of the needle, according as the ship is on the north or south side of the equator, thereby causing serious errors in the compass. Admiral Murray and Captain Penrose, whilst cruising off the Nap of Norway, observed a point difference in the direction of the compass when the ship's head was toward or turned from the land.*

In 1801 and 1802, this important inquiry received fresh impulse from Captain Flinders, who, in the course of his voyage of survey to New Holland, also observed differences in the magnetic needle, when no other cause was apparent than that of a difference of direction in the ship's head. When the ship's head was north or south, the needle was not influenced, but when east or west the difference in the direction of the compass was considerable. Captain Flinders conceives the magnetic force of the ship's iron to be concentrated into something like a focal point, nearly in the centre of the ship, having the polarity of the hemisphere in which the ship is placed.†

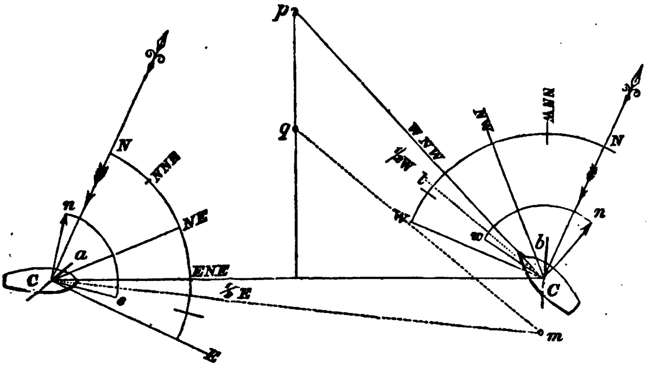
These important facts were, however, again lost sight of, until Mr. Bains, master R.N., published in 1817 a valuable little treatise on the variation of the compass; soon after which, in 1819, Professor Barlow undertook his capital course of experiments (234), with a view of computing and correcting this source of error. The question of local attraction since this period has received abundant and important verification from the labours of our celebrated navigators, Ross, Scoresby, Parry, Franklin, Fitzroy, King, and many others.

305. The errors liable to arise in the reckoning of a ship's course, may, from the local attraction of the ship, be of very serious amount. Let, for example, *a*, Fig. 143, be a vessel close-hauled upon the larboard tack, the wind being true

* Walker on Magnetism: London, 1794.

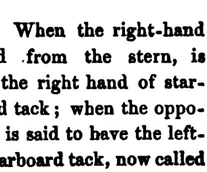
† Phil. Trans. for 1805.

Fig. 143.



north in the direction N C.* Then, since she sails within six points of the wind, her head will be true E.N.E., so that her course, without any other consideration, would be upon the line C c. Supposing, however, that with the ship's head in

Fig. 144.



* In all square sails set upon a cross-yard, pointed to the wind, as represented in the annexed Fig. 144, the rope t which confines the angle of the foot of the sail to windward is called the tack; and the rope s, which holds in the opposite angle to leeward, is called the sheet; these terms apply to either rope, according as they become placed on the one side or the other in respect of the wind. When the right-hand extremity b of the yard, as looking forward from the stern, is pointed to the wind, the vessel is said to have the right hand of starboard tacks on board, or to be on the starboard tack; when the opposite or left extremity a is pointed to the wind, she is said to have the left-hand or larboard tacks on board, or to be on the larboard tack, now called the port tack. The angle which the axial line of the ship makes with the direction of the wind, so that the yard, when trimmed to the wind, may cause the sail to remain full and without shake, and propel the ship, is reckoned in points of the compass, and thus a square-rigged vessel is said to be close-hauled when the axial line of the ship is brought within 6 points of the wind. Cutters with fore and aft sails may be made to sail within 4½ points of the wind, and even less.

this direction the local attraction causes the north pole N of the compass to deviate half a point west, and come into the line *n* C; then the true direction E.N.E. will read on the card as E.N.E. ½ E., for the E. point will then come up half a point, and the card will be canted into the position *n* C *e*.* In laying off the course, therefore, on a chart, for the ship's place, she would be reckoned as sailing on the line C M; and instead of having after a given time arrived at the point *c*, she would be set down as being, say at *m*. Suppose the vessel be now put on the opposite or starboard tack; then, being again trimmed within 6 points of the wind, her head would be really W.N.W. and she sails on the line *cp*. Suppose, however, that in this direction of the ship's head, the local attraction now turns the compass needle half a point the other way, that is, eastward; which it may; and the card is canted into position *n c w*, then the true direction W.N.W. would read on the card W.N.W. ½ W., since the west point would come up in a point;* and she would, in keeping the reckoning by compass, be taken as sailing in direction *c t;* which, laid off from the point *m*, where the ship was supposed to have been tacked, would make her supposed course *m q*; so that, after a second given period of time, the rate of sailing being observed, she would be supposed to have arrived at some point *q*, whereas she would actually be at some point much further northward, for example, at some point *p*. Now, if so great a difference may arise upon a comparatively small difference of half a point of the compass, how great must be the error when the deviation becomes four times that amount! It is therefore not at all surprising that very melancholy cases of shipwreck should have so frequently arisen, without any apparent neglect on the part of the officers of the ship. On the 26th of March, 1803, H.M.'s ship *Apollo*, with a convoy of seventy merchant vessels, sailed out of Cork, and at 3 A.M. on the 2nd of April following, the frigate and forty sail of the convoy found themselves on

* See (312) Fig. 147, p. 169, as applicable to this.

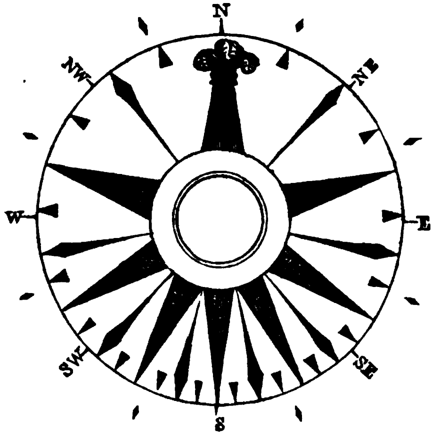
shore on the coast of Portugal, believing at the time they were 180 miles westward of it. The consequence was a most afflicting shipwreck. Another most remarkable instance is to be found in the wreck of H.M.'s frigate *Thetis*, which sailed from Rio the 4th of December, 1830, having on board a million of dollars. The ship's head being south-east by compass, they stood on until the next morning, thinking themselves clear of the land, and the wind coming free, they tacked, and set studding-sails. All at once, after a favourable run, they found the ship against the perpendicular cliff of Cape Frio, the ship running at nine knots. She went stem on to the rock in deep water; of course the bowsprit and all the masts were carried overboard, and the ship became a total wreck.

306. The greatest amount of disturbance hitherto observed in vessels built of wood, does not appear in certain positions to have far exceeded 20°, or about two points, still a very serious error in the course of a ship. In iron vessels, however, the disturbance may be so great as to render the compass next to useless. In the steam-ship *Shanghai*,* driven by a screw propeller, the deviation, with the ship's head south, as observed by Lilley, amounted in the binnacle compass to 171° 34′ W., being more than fifteen points.

It is very difficult to determine all the different arrangements in polarity incidental to the iron of a ship, especially in ships of war and iron-built ships, since every piece of iron in the ship may become magnetic by induction (191), the poles varying as the ship turns into new directions, and changing altogether with the latitude north or south of the equator. The disturbing effect on the compass also will be different under different angles of inclination, as was completely shown by Captain Walker, R.N., in a valuable set of experiments on the *Recruit*, an iron brig. We have hence a very intricate problem to solve. Fig. 145 represents the distortion of the compass in the *Indus*, that is to say, the

* Belonging to the Peninsular and Oriental Company.

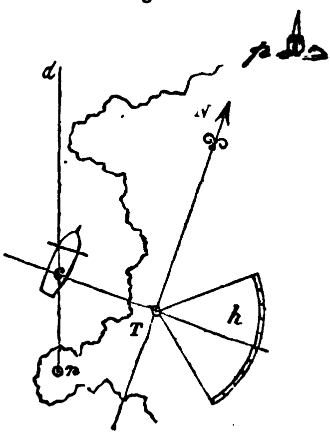
Fig. 145.



direction of the points requisite to a true course. In this figure the position of the regular points is indicated on the outer circle.

307. *Methods of determining the Effect of Local Attraction.*—To ascertain the disturbing effect of local attraction on the compass, the ship must be placed in smooth water in a slack tide, or in a basin, and must be so circumstanced as to admit of being gradually swung and secured in any direction on the 32 points of the compass by means of warps, mooring buoys, or anchors, as indicated in the annexed Fig. 146. The vessel being thus circumstanced, a very

Fig. 146.



distant object *p* is to be selected, and its bearing taken from a convenient station T, on shore, not liable to any magnetic disturbance. This bearing should be taken with a fine azimuth compass, to be employed as a standard compass of observation, and fixed in a given place on board the ship. Suppose the bearing of the distant object *p* at the station T were N. 35° E.: having determined this, we substitute for the compass a theodolite, or the azimuth circle, and adjust it so that the distant object shall read off exactly the same bearing, N. 35° E. The compass is now transferred to the ship, and set upon a firm pillar, in the midship line of the quarter-deck, say at the point C: an observer now takes the bearing of the pillar T on shore, at the same instant that an observer at T on shore takes the bearing of the pillar C on board, which is done by signal. If the ship does not influence the compass, then it is clear that these reverse bearings will coincide in the same line. Thus, if the pillar T bore due east from the ship, the pillar C would be due west from the shore. If this coincidence be not obtained, the difference is the local attraction of the ship. If, for example, whilst the pillar C on board bore due west from the shore, the pillar T bore from the ship east ½ north, that is E. 5° 37′ 30″ N., then the local attraction of the ship directed in the position in which she happened to be placed, would have been such as to have drawn the north pole of the needle 5° 37′ 30″ towards the east, and this would be the local attraction for that position of the ship. In this way, by bringing the ship's head successively upon each of the 32 rhumbs, and taking what are called cross bearings, we determine the local attraction or disturbance of the compass for each point of direction. This was the method first pursued by Professor Barlow, and it is perhaps as perfect as any.

308. The present method pursued in determining the local attraction of H.M.'s ships is somewhat different from this. The bearing of some very distant object *d*, Fig. 146, is first

determined by the standard compass c from the ship's deck, and for the ship's head directed upon each point of the compass; the compass is now taken on shore to some convenient spot *n*, and the same distant point *d* brought to coincide with the observer's eye and the pillar c, from which this bearing was taken on board, the ship being again swung successively upon the 32 points of the compass. If the ship had not disturbed the compass, the bearings should coincide in the line *n* c *d*; if not, the difference upon each point is the local attraction. If the object *d* be very distant, the bearings may be simply taken from the two stations c and *n*, without including the ship, and the difference set down as the local attraction without any sensible error.

309. Mr. R. Stebbing, of Southampton, has lately invented an extremely available and very valuable method of determining the local attraction of a ship, by which much labour is avoided, and time saved. A centre staff T, Fig. 146, with a flag on it, is set up on some chosen place on shore, and a segment *h* of the magnetic circle *h*, of about 100 feet radius, described from this point as a centre, long poles are then set up on this segment at each 5°, and other intermediate shorter poles on each single degree. The line T N of the magnetic meridian being carefully determined, the true bearing of the centre staff T, and its intersection with either of the poles of the segment *h*, are given; with a view to an easy distinction, the poles are either coloured differently, or carry small distinguishing flags. The observer on board at c has now only to take notice what degree the centre staff T cuts upon the circle *h* beyond it, and that is the true bearing; the difference as observed by the compass is the local attraction.

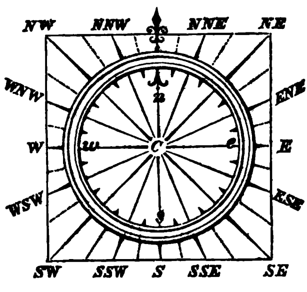
310. *Means of Correcting Local Attraction.*—The means of correcting the compass for local attraction, at present resorted to, are of the following kind:—1°. By determining a table of errors. 2°. By a compass card distorted so as to suit the particular ship (306). 3°. By the introduction of

new forces of disturbance, such as will either make known or compensate the disturbing force of the ship.

311. *Correction by a Table of Errors.*—This method of correction is evidently the first, as it is perhaps the safest, measure we can adopt, and is in all cases indispensable. The ship being swung in the way just described (307), the deviations corresponding to the direction of the ship's head are entered in columns of a table opposite each point of the compass, and the correction in steering a particular course applied. Suppose we required to make good a due E.N.E. course, and that with the ship's head in that direction, the table informs us that the north pole of the needle is drawn by the local attraction of the ship 5° 37′ toward the west, our course then must be E.N.E. ½ East nearly, for that would in fact be the direction shown by the card when the ship's head was in that direction (305).

312. In effecting a corrected course practically by a table of errors, it will be useful to possess what may be termed an indicator, by which the course to be steered by the standard compass, in order to make good any required true magnetic course, may be found mechanically by inspection.

Fig. 147.



This useful instrument may consist of a neat plane of wood Fig. 147, about ten inches square, covered with fine paper, and having the thirty-two rhumb-lines laid off on it, as given in the figure; a moveable compass-card *n e s w* is centrally placed on the board, so as to revolve round a central pin C. Now it is clear, that taking the fixed magnetic lines as the true lines, we may, by bringing any deviation for the north pole *n* of the card to either of these given fixed lines, immediately determine the course by the

standard compass, corresponding to the given course. Suppose, for example, we required to effect a N.E. course, and that in turning to our table of errors we found that with the ship's head in that direction there was an error of a point in easterly deviation of the compass. In such case place the north pole *n* of the card so as to correspond with the N. by E. fixed magnetic line, that is to say, move it eastward 11° 15′; this would then be the actual direction of the card of our standard compass in respect of the true magnetic lines, with the ship's head at N.E., and would hence bring the N.E. by N. point of the moveable card upon the fixed N.E. line, which shows, that to effect a true magnetic N.E. course, we must steer N.E. by N. by the standard compass.

We may, in a similar way, find the actual direction of the ship's head corresponding to a given course by the standard compass. Suppose, for example, the course by standard compass was N.N.W., and that with the ship's head in that direction, the needle deviated half a point West, set the moveable card to the deviation by turning the north pole *n* to the left hand, half a point, which will bring the N.N.W. line of the moveable card to N.N.W. ½ W. of the fixed chart, which will be the actual direction of the ship's head when steering N.N.W. by the standard compass. These are selected as illustrations of more complicated cases.

313. *Correction by Distorted Card.* — The ship being swung upon the different points of the compass, a card is marked off, such as on trial will correspond with the true magnetic direction of the ship's head, as shown (306) in Fig. 145, and by which the ship is to be steered. This method has been found very available and satisfactory, the objections are, that the irregular distances of the points of the compass confuse the helmsman, especially in steering ½ and ¼ points, and that it is almost impossible to take an accurate bearing with such a card. Captain Sparkes, however, who has lately obtained a patent for a card of this kind, has ingeniously applied a divided circle to

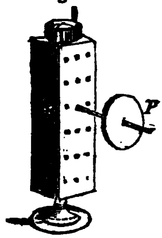
the verge of the compass, by which, when set to the course steered, any bearing may be taken. The idea of a corrected card appears to have been also suggested by Captain Milne, R.N., in an interesting paper on the subject of local attraction so long since as the year 1832.

314. *Correction by Compensating Disturbing Forces—Barlow's Plate.*—We are indebted to Professor Barlow for the first attempt ever made to correct the local attraction of a ship by a mass of iron placed in the vicinity of the compass, so as to introduce into the system a new disturbing force, which, acting at a given point, would produce the same effect on the needle as that of the iron of the vessel. In order to understand clearly this kind of correction, we must observe, that all the laws which Professor Barlow had determined in his researches concerning the operation of regular masses of iron on the needle (234), he found to obtain for irregular masses, whether as a system under the form of detached masses, as in a ship, or under any irregular form. In all cases a close approximation to the action of the system on the needle is arrived at, on the supposition that the force proceeds from two centres indefinitely near each other in the general centre of attraction of the mass, and that in iron bodies the magnetic force is confined to their surface.

From the first of these principles, confirmed by subsequent experiment, we may infer that the centre of action of all the iron of a ship, and the ideal line joining this centre with the centre of the needle, would be constant in all parts of the world; by the second we infer that a mere plate of iron may be so placed in this line as to produce an action on the needle equal to that of the ship; so that the disturbance produced by the plate being found experimentally, the disturbance due to the ship would be known. This principle was first employed by Professor Barlow in the following way:—The deviations of the compass being determined as before (307), the compass is taken on shore to a given

station T, Fig. 146, and there placed on a cubical box or case G, Fig. 148, moveable on a vertical axis into any azimuth (149). A circular double disc of iron P, composed of two thin plates of iron, fixed parallel to each other on an horizontal axis P, with intervening wood, and termed a compensator or correcting plate, is then applied at some point determinable by experiment at the side of the case, so as to project from it, and at some given distance in respect of the compass; the whole is now swung into various azimuths, and the disturbance of the plate P observed in each, as before done in respect of the ship; by a very few trials, such a position of the plate can be found as will cause it to produce precisely the same disturbances as those observed in the ship. The plate being capable of adjustment on the axis P as to distance horizontally, and on the case G as to height vertically, the position of the centre of the plate P is now carefully marked, and the compass replaced in the ship. If the plate be now applied as before, then, as is evident, the amount of disturbance will be twice as great; since the compass will not only deviate by the action of the ship, but also by the action of the plate. It is this double disturbance, however, which furnishes the required correction, because the new disturbance caused by the plate is exactly equal to the existing disturbance of the local attraction. Thus supposing the ship's head being N.E., the variation (149) as taken with the azimuth compass to be, without the plate, 22° 30′ West, and taken with the plate 29° 27′ West, then the difference 6° 57′ West is due to the plate; but this, as we have seen, is exactly equal to the iron of the ship. We must, therefore, to obtain the true variation, apply this correction to our first observation, which will make it 15° 33′ West; and to make a true N.E. course by the compass, we must steer N.E. $\frac{3}{4}$ E., that is N.E. 6° 57′ E.; the

Fig. 148.



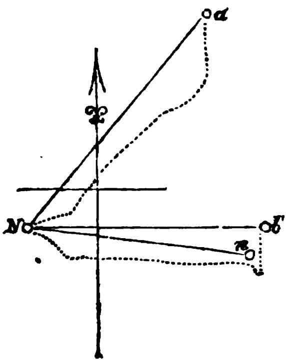
quantity by which the iron of the ship has drawn the north pole of the needle west, as shown by the plate.

315. *Balance of Errors by Barlow's Plate.*—Since the correcting plate P, Fig. 148, can double the disturbance when placed in a given position in respect of the compass, we may infer that, by changing its position, an opposite point may be found in which the plate would exactly balance the local attraction by a disturbance in an opposite direction; and such is found to be the case, or at least approximately. In applying the plate to the standard compass, either with this or the preceding view, the several bearings for each point (307) must be examined, when two opposite points will be commonly found in which the bearings nearly coincide, the mean of these must be taken as indicating a line of neutrality in the ship; the direction of the line must be noted, and in some point of this line the compensator must be ultimately fixed. To determine its exact position, Professor Barlow has drawn up a general table of local attractions comprising all possible limits of disturbance for every class of sailing ship in the royal navy built of wood, in which are found the limits of disturbance applicable to the given vessel; opposite these limits are two numbers, one representing the distance of the centre of the plate below the pivot of the needle, and the other its distance from the plumb-line or vertical passing through the pivot of the needle. At this depth and distance in the line of no attraction, and abaft the compass, the compensator will balance all the disturbance arising from the iron of the ship, so that on swinging the ship (307) the needle will be found without error.

316. This method of correcting the compass for local attraction, if not absolutely perfect, has proved eminently successful in practice; and why it has been discontinued in the royal navy, without further investigation, it is difficult to say: its great importance may be inferred from the annexed diagram, Fig. 149, which represents

the true and calculated courses of H.M.'s ship *Griper*, between the 25th and 26th May, 1823, as laid off from the ship's log. In this diagram, N denotes the ship's place at noon by astronomical observation, 25th May; and *n*, the place of the ship at noon, also by astronomical observation on the next day, 26th May. According to her calculated place by the uncorrected compass, she would have been found at *a*, but by the compensated compass at *b*, very near her true place, making a difference of 35 miles of latitude, sufficient to have shipwrecked the vessel (305).

Fig. 149.



317. *Correction by Magnets.*—Some important practical observations having in 1835 been made by Captain Johnson on an iron steam-ship, the *Garry Owen*, from which it appeared that the ship operated upon a compass-needle placed outside the ship, after the manner of a permanent magnet, the Astronomer Royal, Professor Airy, was led, in July, 1838, to undertake an extensive experimental and analytical investigation of the whole subject, with a view to discover such general laws of the magnetic disturbance in iron ships as would enable him to correct the local attraction. This fine physical and mathematical inquiry will be found in the Transactions of the Royal Society for 1839. It would be impossible, however, within the limits of so unpretending a work as this, to do full justice to Professor Airy's capital paper; we can only hope, therefore, to treat it in such a general way as may apply to the question before us.

Whatever be the number or direction of the magnetic bodies in a ship, the effects on the compass may be resolved into three forces,—one directed to the ship's head, one toward the starboard side, and one directed downward verti-

cally. If we represent the effects which depend solely on the arrangement of the ship's iron by two constants P and N (that is to say, forces which do not change, and which may here be determined, and which become the multipliers or coefficients of certain unknown quantities) the one, P, being a coefficient upon which the force transverse to the keel depends, and the other, N, a coefficient upon which an induced force, similar to that of permanent magnetism, depends; and if the arrangement of the iron be symmetrical with respect to the keel, and the compass placed in the middle of the breadth, then taking the deviation of the north end of the needle in an east direction, it may be represented by $P \times \sin. 2A + N \times \text{tang.}\ \delta \times \sin. A$; in which A is the azimuth of the ship's head reckoned eastward, and $\delta =$ the dip. Should the general mass of the iron be at the same height as the compass, or should different masses of equal magnitudes constituting the iron of the ship have equal elevations and depressions in opposite azimuths, then the constant N will vanish. The constant P will vanish when the general mass of the iron is below the compass, or when equal masses are 90° distant, as seen from the compass.

In the application of Barlow's plate, Professor Airy conceives that it only neutralizes the term dependent on N, but not that dependent on P. To obtain a perfect compensation, we must place another plate at the elevation of the compass in an azimuth of 90°, either to the right or the left of the first plate as commonly applied; in this case P will be also compensated.

Besides these coefficients P and N, we have a third also to consider as depending on the absolute diminution of the directive force in a north and south line, and which we may call M; this term is greatest when the iron mass is above or below the compass, and least when at the level of the compass.

The forces to be considered, according to the results of his inquiry, estimated by their action on the north pole of the needle, are four; viz. the force of terrestrial magnetism

towards the north = unity; permanent magnetism in direction of the ship's head; permanent magnetism to starboard side; induced magnetism to the starboard side. This last force may be resolved into induced magnetism toward the north, represented by $-M + P \times \cos. A$; and induced magnetism toward the east, represented by $P \times \sin. 2A$.* By far the most considerable of the disturbing forces are those dependent on permanent magnetism: these were not found to change in whatever position the ship was swung. The induced forces appear to be comparatively small.

The horizontal intensity in the ship directed in the line of the compass, as also the terrestrial intensity on shore taken = 1, is determined by the needle of oscillation (254); the ship being swung into different positions.

Professor Airy having brought the various forces of disturbance under the dominion of theory and calculation, proceeds to destroy them by the introduction of other and opposite disturbing forces.

The longitudinal and transverse forces may be corrected by the action of a single magnet placed at a given distance below the compass, with its poles so directed as to draw the north end of the needle toward the ship's head and starboard side; or otherwise by two distinct magnets, which is much more convenient. The induced force toward the east, or $P \times \sin. 2A$, may be corrected by placing a mass of iron on a level with the compass, either on the starboard or port side: with these correctors duly applied, the compass was found free of disturbance.

The only chance of error in this correction is the uncertain value of the induced force N, and its variable character in different latitudes; there is, however, every reason to suppose that it is extremely small, and may, in

* The induced force we have called N is omitted here, being intricately combined with the permanent magnetism in the direction of the ship's head; the force M also, not producing any effect in an east and west direction, is omitted.

certain dispositions of the iron of the ship, vanish altogether, so that the correction for one latitude may, without sensible error, be used in all latitudes.

The correction of the compass then, in iron ships, becomes reduced to the compensation of force of permanent magnetism toward the head; of permanent magnetism toward the starboard side; and the term depending on P, the effect of which in an easterly direction is represented by P × sin. 2 A; omitting N as being small, and M because it does not disturb the compass.

318. The practical method of effecting these corrections is to swing the ship as before upon the cardinal points, then, by means of two magnets and a mass of iron, to correct the disturbances. The magnets are placed by trial upon some point in one of two lines carefully determined, one parallel to the keel, the other at right angles to the keel; these lines are either traced on the deck, or on the ceiling below the deck timbers. If the ship's head be north or south, and the transverse magnet be shifted by trial until the compass points correctly, it will be certain then that the force to or from the starboard side is compensated. Similarly, if the ship be swung east or west, the longitudinal magnet is shifted until the compass again points correctly; the force to or from the head is now compensated. To correct the force represented by P × sin. 2 A, the ship must be swung into the intermediate points N.E., N.W., &c., and the compass made to point correctly by means of a mass of iron; an iron chain, for example, placed by trial, either on the port or starboard side.

As it is requisite in this operation to correct the compass simultaneously with the observation of the deviation, the very ingenious method pursued by Mr. Stebbing, of Southampton (309), is of the greatest value in this case.

Some vessels are more easily managed than others. The compasses in one vessel may require a single magnet only; others require two, with the addition of a box of iron chain.

The *Ripon* has two magnets and chain for each compass. The *Pottinger* had a single magnet only, aided by a chain. The *Ariel's* compass was corrected by one magnet only, without any auxiliary aid.*

319. Many objections have been raised, as may be easily imagined, to these methods of compensating the forces, disturbing the compass by the introduction of other disturbing forces, such as the liability of the relations of the magnetic forces to change with change of place and with time; the influence of changes of temperature on the correcting magnets, as also the liability of the magnets themselves to vary in power, such objections are of course inseparable from this kind of investigation, and we can only determine their validity by experience. So far as experience extends, it cannot be denied, but that the compass as corrected in iron ships by Professor Airy's method, has, upon the whole, acted remarkably well. The commanders of the iron ships *Sultan*, *Pottinger*, *Harbinger*, and many other large steam-ships, report most favourably of the efficiency of their compasses thus corrected. The latter vessel, corrected by Lilley, has been in a southern latitude, without finding any material change in the balance of the forces. We cannot certainly consider the question to be so definitely determined as to render all further observation unnecessary; it is very important, as stated by Professor Airy, to subject the vessel from time to time to further examination, and carefully note all the changes which are liable to occur. There is little doubt but that compasses corrected by permanent magnets are affected by time and by geographical position, but still not to such an extent as is likely to lead to any very sensible error, or an error which may not be provided against. Some very interesting remarks by Mr. J. R. Stebbing, on this important question, will be found in the "Artizan" for August, 1850. Mr. Stebbing conceives that "the practical difficulty of correct-

* "Artizan" for August, 1850.

ing compasses for iron ships is overcome, and that such ships are as safely navigable as ships built of wood." Messrs. Lilley also, who have corrected the compasses of more than fifty iron ships by permanent magnets, and by a method of observation of their own not generally known, also report confidently on the efficiency and safety of the principle deduced by the Astronomer Royal.

Ships, however, destined for long voyages, should still depend materially on a table of errors (311), registered for a standard compass, whatever other method of correction of the compass be resorted to :—corrected cards (313) are decidedly useful, especially in iron ships, and may be employed with advantage in conjunction with other means to determine the true magnetic course.

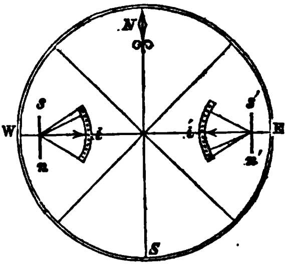
320. The following are a few important facts as deduced by Mr. Stebbing, from his experience of iron ships :—

1. A compass may be very true on one or several points, and greatly disturbed on others. 2. The errors in one ship are no guide to the errors of another. 3. The errors are least toward the middle of the vessel. 4. Every iron ship is a magnet in itself: some have the north pole aft, and some the south. The magnetic axis is frequently determined diagonally through the ship. 5. There are in all iron ships two points, either opposite or nearly so, at which there is no error; there are other two points where the error is the greatest. An error will not sometimes alter 3 degrees in a range of 5 points, and then change 30 degrees in the next 5 points. 6. The deviation is always an accumulating error or the reverse: it runs, 1, 3, 7, 12, 17, 26, 30, 32, 33, 31, 28, 24, 20, 17, 13, 9, 6, 3, 0; but never, for example, thus—3, 7, 4, 10, 8, &c.

321. We must not dismiss this most important subject without a brief notice of an ingenious compass by Mr. St. John, of Buffalo, United States of America, and which was rewarded with a medal at the late Great Exhibition: the object of the arrangement is to indicate the amount of

local attraction, and the deviation of the compass actually present at any moment. This invention is shown in Fig. 150, in which N E S W represent the suspended card and needle: *n s*, *n′ s′*, are two short slender needles, delicately set up on vertical axes and attached to the compass-card, one on each side of the centre of the great needle; and on the east and west line, these small needles, termed satellites, carry fine indexes *i*, *i′*, made of reed, centrally fixed to them and at right angles to their direction, so as to indicate on graduated arcs *i*, *i′*, any deflection to which they are subject. Supposing the compass to be in the true magnetic meridian, the three needles will be parallel, but the small needles will stand with their poles *n s*, *n′ s′*, reverse to the poles S, N, of the large needle (14, 31). If under these circumstances the compass-needle N S deviate from the true meridian, then the position of the small needles *n s*, *n′ s′*, will vary from parallelism, and indicate on their respective arcs *i*, *i′*, the amount of deflection to which the compass is subject; at least this is the conclusion arrived at by the inventor. The notion is extremely ingenious, and the contrivance as a mechanical arrangement very elegant: it requires, however, much further investigation before the principle can be considered as being perfectly available.

Fig. 150.



CONCLUSION.

322. We have now gone through, in as comprehensive a way as the limits of our work will permit, all the great leading facts of ordinary magnetism, theoretically and practically considered, and have at the same time entered upon

the several important physical questions to which they have reference; we have now merely to advert in conclusion to some of the more recent applications of this branch of science in furthering the progress of civilization, or in contributing to the wants of mankind.

323. The next great practical application of magnetism, after the mariners' compass, is the auxiliary means it has afforded in the construction of the electrical telegraph, and without which that wonderful contrivance could never have been made so perfect as it now is. For although the electrical current is the great element by which the transmission of thought is effected between persons separated by almost any amount of distance, yet it is by the varying motions and positions of the magnetic needle, ever obedient to the wire affected by the current action (40), that we owe the interpretation of the ideas or thoughts, concealed and conveyed as it were through the wire. Having already explained in our volume on electricity* the general telegraphic agency of the electrical current, and the means afforded to its transmission through wires continued through various points of space, we shall limit ourselves here to a notice of the more immediate part of this wonderful contrivance so far as it depends on common magnets, the various motions of which constitute, as it were, the language of the instrument.

324. It will be immediately seen by reference to the phenomena of electrical wires and magnetic needles, already explained (40, 41, 46), that one or more needles, finely set upon an axis, either vertically or horizontally, may be caused to assume various positions, and may be deflected any number of times successively, either to the right hand or to the left, and almost at any point of distance from the source of power, provided the means of communication of the current be afforded; and thus we have an interpretation of events at

* Rudimentary Electricity, second edition, p. 191.

hand, according to any preconcerted code of signals. We have likewise seen (53) that by making or breaking contact with a voltaic circle, a piece of soft iron may be vigorously attracted toward the poles of an electric magnet, or be again easily separated from it. We have here then a further source of motive power at a distance, by which machinery may be set in motion, alarms sounded by means of bells, and other audible signals effected. When a single needle is employed, the code is termed the single-needle code. The arrangement consists of a magnetic needle, or set of needles, *a*, Fig. 152, enclosed within a galvanometer coil (46), and set on an axis; the axis projects horizontally, and carries a vertical index-needle, *b*, in front of a silvered brass dial; the alphabet is engraved on the dial, right and left of the index-needle, as in the annexed Fig. 151.

Fig. 151.

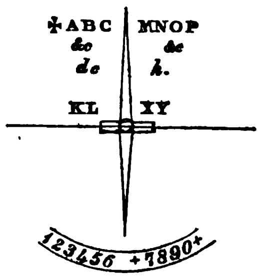
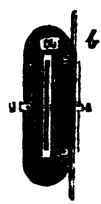


Fig. 152 represents the position of the galvanometer coil and needle *a* behind the plate, with the axis and needle *b* in front of the plate. The two needles are placed with poles reverse to each other (29), and both are more or less acted on by the coil. In order to give the system a tendency to the vertical position, a slight preponderance in weight is given to the lower extremities of the needles. The extent of deflection is limited by pins fixed on the dial.

Fig. 152.



325. The letters are indicated by successive deflections, or beats of the needle, communicated by the current from a distance to the galvanometer arrangement behind the plate and in given directions; thus the letter L is indicated by four successive deflections, right, left, right, left. The last beat is always the end of the word, and is a left-hand beat.

326. In the double-needle code two galvanometers are employed, and two index-needles placed parallel to each other; the double-needle code gives, of course, increased facility, as admitting of a greater number of combinations. In this arrangement two galvanometers (46), with their respective needles, stand side by side; one is called the left needle, the other the right needle. Now we may either deflect the right needle or the left, or both at one time, causing their upper or under points to converge to the same letter, and furnishing signals which may easily correspond with a given code; thus, the upper half of the left-hand needle twice deflected to the left may be A, three times B, once to the right and once to the left C, and so on. In order to spell the word HEN, for example, a first beat is made with the right needle for H, then a second with the left needle for E, now a third beat with the right needle signifying N; finally, a fourth beat with left needle, corresponding to the symbol ✠, signifying the termination of the word. In order to render these movements of the needles effectual, there are two handles below the dial by which the connection with the voltaic battery (40) can be, by means of a particular mechanism, rapidly made, so as to cause the current to flow in any direction (41). In the double-needle arrangement everything is, of course, doubled.

327. Professor Wheatstone, to whom we are mainly indebted for the needle apparatus, also contrived a method of signalizing the letters themselves. This is effected by a circular dial, or disc, set on a central axis, and on which the alphabet is engraved, as also the numerals. The circumference of this plate, taken edgewise, has a succession of insulating and conducting intervals, so that in turning it round we effect or break contact with the battery, by means of a spring pressing against the surface. Any series of letters we choose to make appear at a given opening in a case covering the dial will be repeated at a distance by a similar dial. This is effected by the temporary magnetizing of soft

iron, in making and breaking contact with the battery (53) as we turn the disc round to a particular letter. By this, as in the motion of the alarm-bell, a motive force is obtained at a distance, the mechanism operated on being so arranged as to turn by electro-magnetic action, any required letter of the distant dial to the opening in its corresponding case. Thus, if we signalize at any station the letters F I R E, in succession, then the same will successively appear upon the opening of the dial at a distant station, say of 100 miles. This species of telegraph has been termed the mechanical telegraph, in opposition to the former, which has been termed the needle-telegraph, and which is that commonly employed in this country.

328. Although to an observer the manipulation in working the telegraph dials may appear complex and perfectly incomprehensible, and the delivery of a message at the rate of eighteen words per minute from a hundred miles distant quite marvellous, yet the practice of the operations is very soon acquired by the clerks engaged in this department of our railways; indeed, after great experience, the manipulator can work with a blank dial; and the particular clerk employed at the distant station to transmit the message, may be actually known by his characteristic deflections of the needles right or left. One is firm in his signals, another sharp and rapid; one patient, another hasty.*

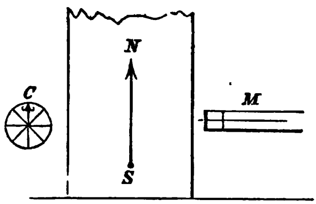
329. The application of magnetic influence in determining distance through otherwise impermeable matter, or the thickness of solid rock or other substance, may be considered as another valuable application of ordinary magnetism, especially in mining operations. We are indebted to the Rev. Dr. Scoresby for this method of measuring distance.

It is evident that since the deviations of a delicate needle, by the influence of a magnet placed in the line of its

* Walker on Telegraphic Manipulation.

centre at right angles to the meridian (134), may be taken as a measure of the force of the magnet; so, conversely, the same deviations, under similar conditions of direction, must correspond with equality of distance; that is to say, supposing the intervening matter to be permeable or transparent to magnetism. If, therefore, we determine for a given magnet and needle a table of deviations corresponding with certain distances between the centre of the needle and magnetic pole when placed in a given position, we may thereby determine the distance at which the magnet is operating through solid matter, by observing the deviation produced.

Fig. 153.



Let, for example, C N M S be a mass of solid rock, S N the direction of magnetic meridian, and that the walls of the mass lie in that direction; let C be a delicate compass, finely divided, and placed on one side of the rock, and M a magnet placed perpendicular to its centre on the other; the compass-needle will then be deflected a certain number of degrees; from which the distance may be found either by the table, or by bringing the magnet round to the side of the compass, and finding experimentally the distance at which the same amount of deviation will be produced. If the intervening rock should lie oblique to the meridian in direction S N, and the compass-needle become oblique to the walls, we must then deflect it by the influence of an auxiliary magnet, so that it may stand parallel to the walls of the rock, and then proceed as before. By a careful preparation of the apparatus, Dr. Scoresby has succeeded in measuring distances of 126 feet to within a very small fractional amount.*

330. Ordinary magnetism is employed for the separation

* Edin. New Phil. Journal, April, 1832.

and collection of particles of iron, mixed with other finely-divided matter, by means of permanent magnets, as also to the most important and humane purpose of catching up, in a similar way, the destructive dust of steel, which, in the grinding of needles, is liable to find its way into the eyes and lungs of the workmen, thereby producing diseases of a serious character, more especially of the lungs.

331. Common magnetism is in this way made available in a machine for separating from impurities disintegrated particles of certain rich ores of iron found in Canada, and which average from 60 to 70 per cent. of pure iron. These ores, by exposure to the wearing action of the atmosphere, freely break up into small grains; they are then stamped and dressed, after which the magnet is used to act on the disintegrated particles, and thus separate the iron from its gangue.

THE END.

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